

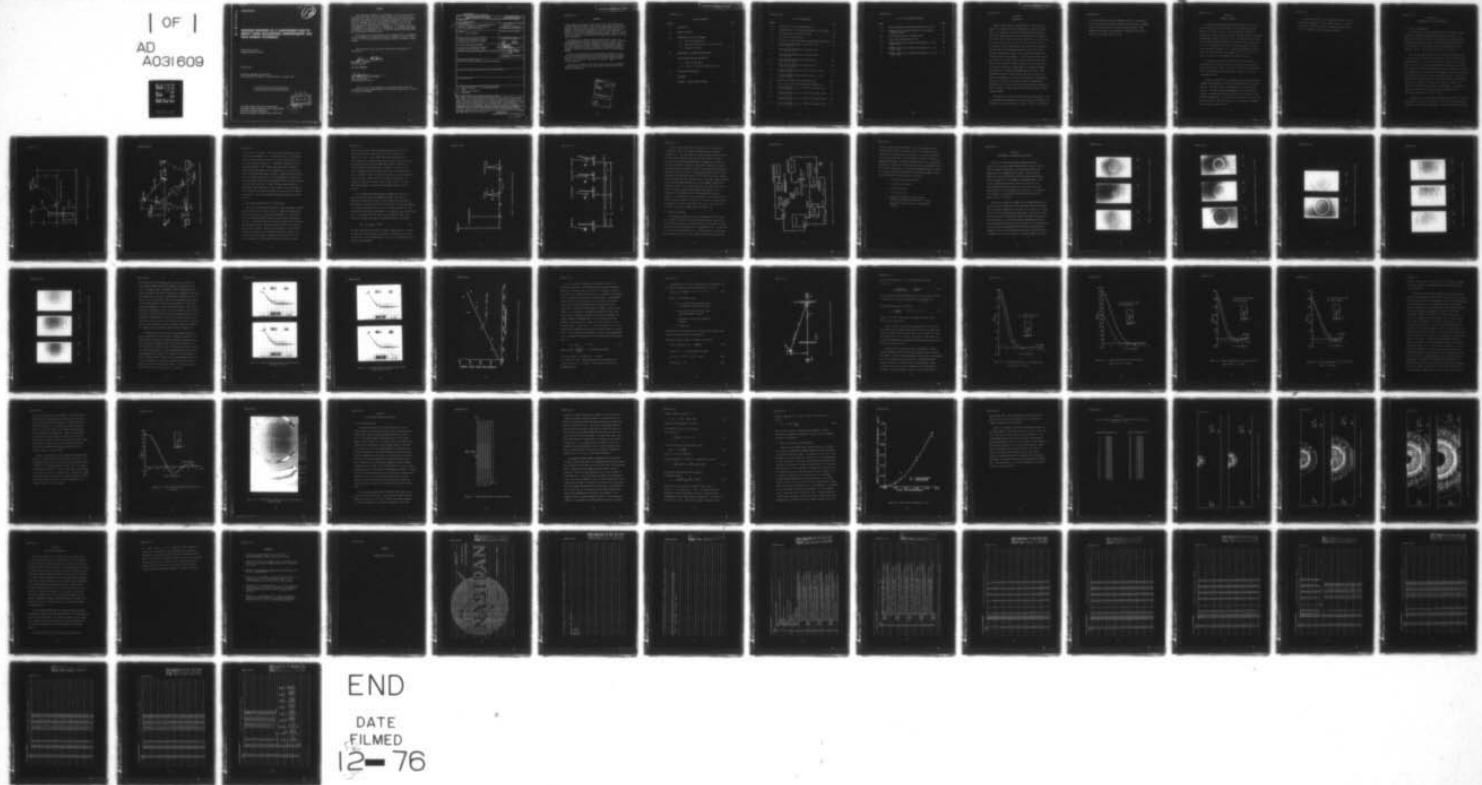
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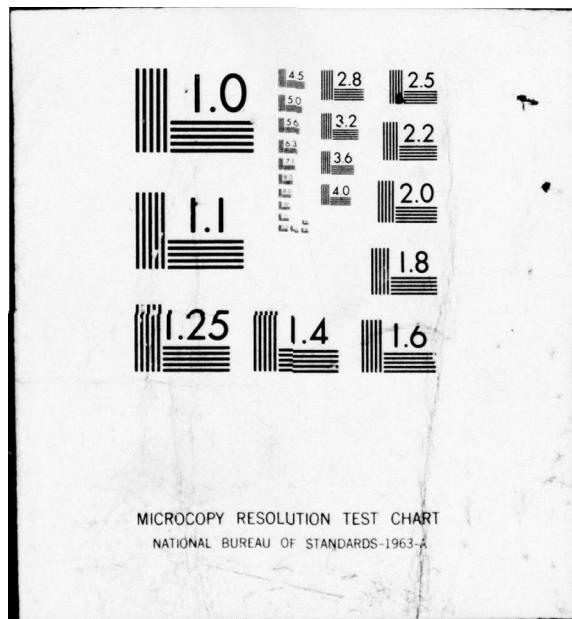
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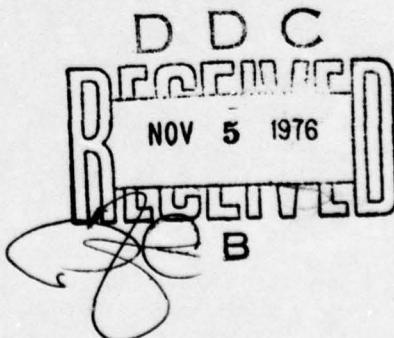
# TRANSIENT RESPONSE OF A CANTILEVERED PLATE TO IMPACT USING HOLOGRAPHIC INTERFEROMETRY AND FINITE ELEMENT TECHNIQUES

PROPELLION BRANCH  
TURBINE ENGINE DIVISION

AUGUST 1976

TECHNICAL REPORT AFAPL-TR-76-56  
FINAL REPORT FOR PERIOD 1 JANUARY 1976 TO 1 AUGUST 1976

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AIR FORCE AERO PROPULSION LABORATORY  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report covers work carried out at AFAPL's Turbo Structures Research Laboratory (TSRL) on the transient structural response of an isotropic cantilevered plate subjected to normal impact by a ballistic pendulum. The program was a combined experimental/analytical effort. The experimental portion utilized a pulsed ruby laser to obtain holographic interferograms of the plate's deformation following impact. The analytical portion of the work consisted of mathematically modelling the plate using finite element techniques and studying the model's response to impact using the general purpose finite element program, NASTRAN.		

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## FOREWORD

This report covers work carried out at AFAPL's Turbo Structures Research Laboratory (TSRL) on the transient structural response of an isotropic cantilevered plate subjected to normal impact by a ballistic pendulum. The effort was intended as a vehicle for evaluating the methods of pulsed laser holography and finite element analysis as they relate to the study of transient structural dynamics. This is an area which bears directly on the problem of foreign object damage to turbine engine components.

The program was a combined experimental/analytical effort. The experimental portion utilized a pulsed ruby laser to obtain holographic interferograms of the plate's deformation following impact. The analytical portion of the work consisted of mathematically modelling the plate using finite element techniques and studying the model's response to impact using the general purpose finite element program, NASTRAN.

The work was performed in the Turbine Engine Division of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio under Project 3066, Task 12, and Work Unit 21. The effort was conducted by Dr. James C. MacBain of the Propulsion Branch.

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## SECTION I

## INTRODUCTION

Foreign object damage in both military and civilian turbine engines is a seldom but serious problem both in terms of cost and safety. For example, the Air Force Inspection and Safety Center states that 2816 birdstrikes have been reported Air Force-wide between 1966 and 1973. These birdstrikes resulted in a loss of 7 lives, 14 aircraft, and a cost to the Air Force of \$74 million dollars. These figures serve to underline the fact that there is a definite need for both basic and applied research in the area of impact-tolerant turbine engine blading. More sophisticated design tools and impact theories are required. In this vein, this report covers work carried out at AFAPL's Turbo Structures Research Laboratory (TSRL) on the transient structural response of an isotropic cantilevered plate subjected to normal impact by a ballistic pendulum. The program was a combined experimental/analytical effort. The experimental portion utilized a pulsed ruby laser to obtain holographic interferograms of the plate's deformation following impact. The analytical portion of the work consisted of mathematically modelling the plate using finite element techniques and studying the model's response to impact using the general purpose finite element program, NASTRAN.

The specific aims of this research effort were threefold. First, the advantages and disadvantages of using pulsed laser holography for transient structural analysis were studied. Second, it was intended

to use the experimental pulsed holography results as a verification of results obtained analytically using the computer program, NASTRAN. Finally, the research effort served to provide knowledge of and experience with pulsed laser holography - information that will be useful in future TSRL research efforts.

## SECTION II

## SUMMARY OF RESULTS

An aluminum cantilevered plate measuring 3"x7"x.1875" was struck with a ballistic pendulum consisting of a .65" diameter steel ball attached to a wire on a pivot. The resulting plate response was measured for a specified time after impact by double exposure holographic interferometry using a pulsed ruby laser. The plate's normal displacement was experimentally determined for times after impact ranging from 2 to 33 $\mu$ s. Photographs of the double exposure holograms from these tests are shown in Figures 4.1-4.5. The normal displacement based on four of the test runs (times after impact of 4, 6, 12, and 18 $\mu$ s) is shown as a function of plate geometry in Figures 4.10-4.13.

The flexural wave velocity was computed from the holographic interferograms by plotting the plate wave position versus time after impact and was found to be  $C_f = .102 \text{ in}/\mu\text{s}$ . This is in good agreement with the theoretical Rayleigh surface wave velocity of  $.112 \text{ in}/\mu\text{s}$  - a difference of 8.5%.

A parallel numerical study was conducted using the finite element computer program NASTRAN to compute the cantilevered plate's transient response. The results were in good agreement with the experimental findings. The plate's normal displacement based on finite element analysis is shown plotted in Figures 4.10-4.13 as a function of plate geometry (dashed lines). Contour plots of the plate's normal displacement for different times after impact were also generated by NASTRAN and are shown in Figures 5.3-5.5.

The study demonstrated the feasibility and utility of using pulsed laser holography to study transient structural response. In addition, it provided increased confidence and experience in the use of NASTRAN's transient analysis capability.

## SECTION III

## EXPERIMENTAL SET UP AND PROCEDURE

## 3.1 Physical Configuration

The test piece for the experimental portion of the impact analysis program was a 6061-T6 aluminum plate measuring 12" in length, 3" in width, and 3/16" thick. The plate was fixed between two steel blocks having a total weight of 33 lbf such that it was cantilevered and had a free length of 7". The weight of the cantilevered portion of the plate was .394 lbf. The plate and jig are shown in Figure 3.1.

The plate was impacted normally by a steel ball weighing .043 lbf at a point lying on its long axis and located 3" above its fixed end as shown in Figure 3.1. The ball was soldered to a thin wire that in turn was fixed to a pivot located a distance above the impact point forming what is known as a ballistic pendulum. The impact sequence was initiated by suspending the steel ball from an electromagnet which was then switched off allowing the ball to swing down and strike the plate. Just prior to impact, the ball interrupted a continuous wave laser beam passing behind the plate (see Figure 3.2) causing a photo diode to transmit a 10V signal that initiated the pulsed laser firing sequence. The timing and electronics involved in the pulsed laser firing sequence will be addressed in more detail in a later section.

The optical set up for making the hologram is also shown in Figure 3.2. The placement of the optics is typical of that used to make transmission holograms with an off-axis holographic set up, and the reader is referred

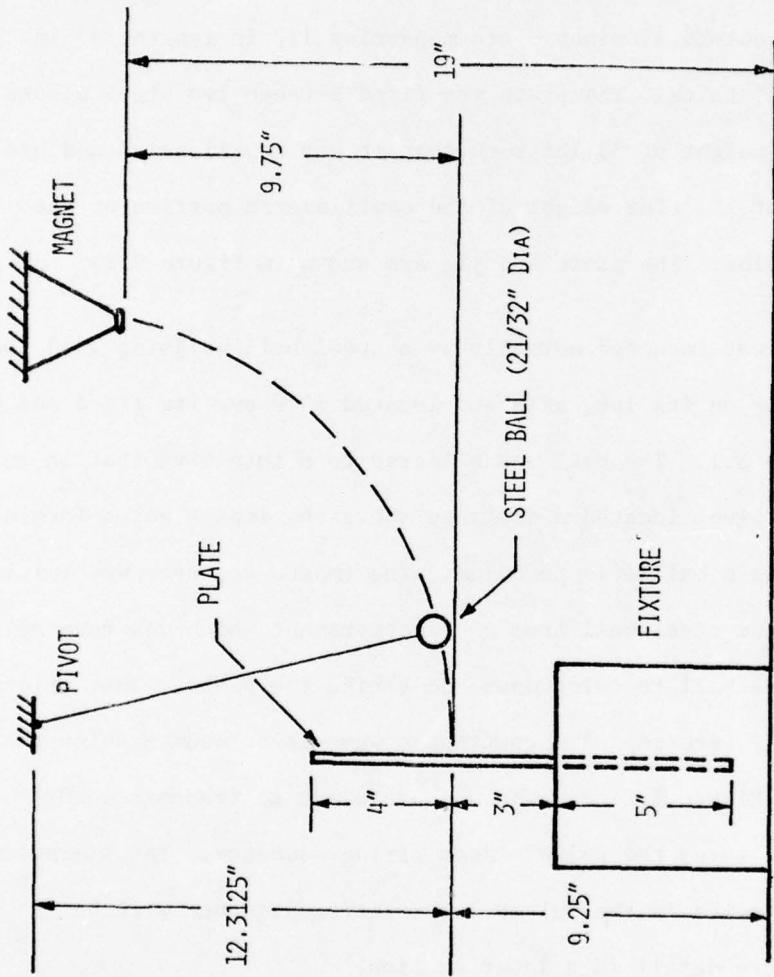


Figure 3.1 - Cantilever Plate and Pendulum Geometry

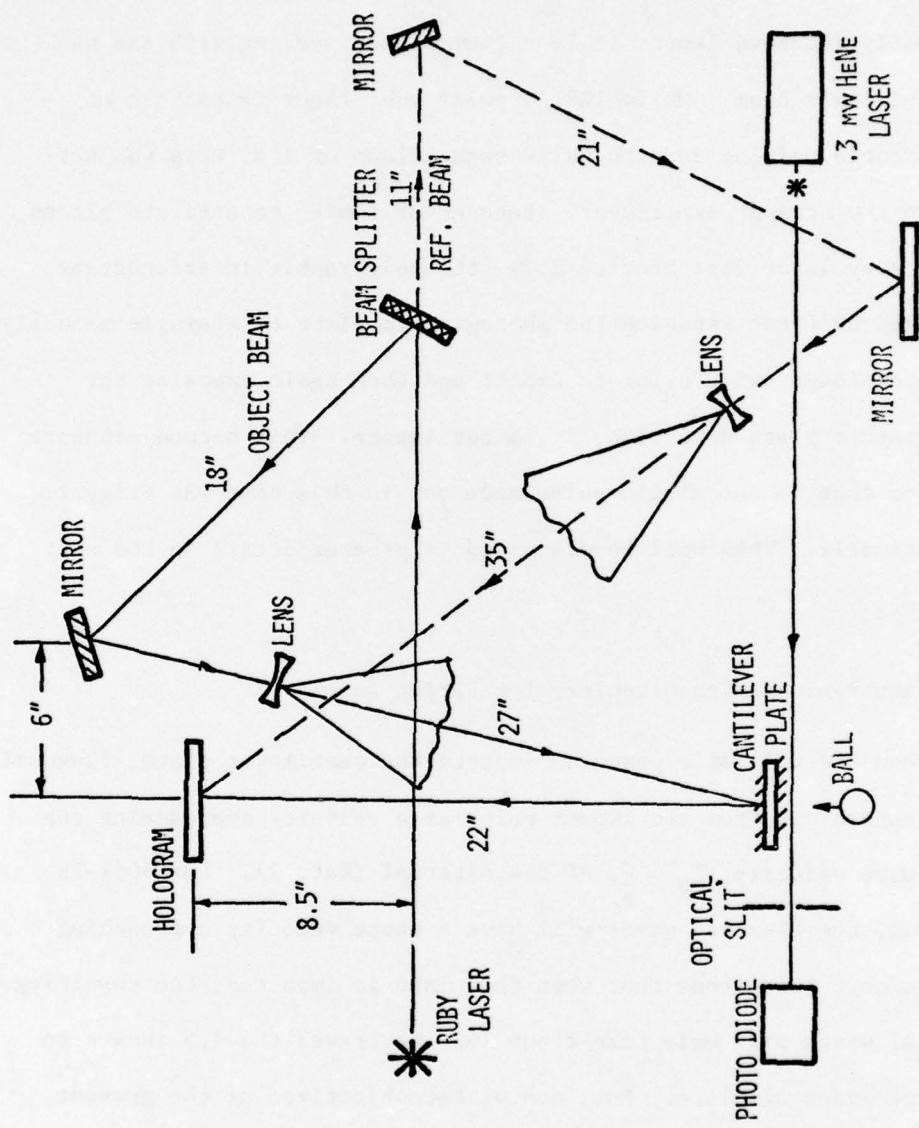


Figure 3.2 - Experimental Set-up for Making Holographic Interferograms

to Reference 1 for details. The holograms were made using a pulsed ruby laser (Apollo Model 22HD). The laser puts out 2.5 joules/pulse, 20-50ns in width, which necessitates the use of dielectric mirrors and doubly concaved lenses (F.L. = -40mm) when working with the un-expanded laser beam. While TSRL's pulse ruby laser is capable of rapid double pulsing down to pulse separations of  $1\mu s$ , this was not done in the present experiment. Because of timing constraints placed on the ruby laser (see Section 3.2), the holographic interferograms were made by first exposing the photographic plate to a single manually initiated laser pulse prior to impact and then again exposing the photographic plate some time,  $\Delta t$ , after impact. This second exposure was also done in the single pulse mode but in this case was triggered automatically. This will be discussed in greater detail in the next section.

### 3.2 Electronic Timing Circuitry for Firing Laser

When the ballistic pendulum impacts the cantilever plate, flexural waves spread out from the impact point at a velocity approaching the shear wave velocity,  $C_s = \frac{G}{\rho}$ , of the material (Ref. 2). For 6061-T6 aluminum, the flexural waves will have a phase velocity approaching .114 in/ $\mu s$ . This means that when the plate is impacted, the resulting flexural waves will only take about  $16\mu s$  to travel the 1.5 inches to the free sides of plate. Now, one of the objectives of the present study was to analyze the plate deformation just after impact, i.e., at times after impact prior to significant wave reflection off the plate's boundaries. For acceptable results, this places an upper

bound on the time for firing the second laser pulse of about  $30\mu s$  (wave reflection will occur off the closest free edges of the plate at  $t = 16\mu s$ ). This in turn places some constraints on the firing sequence for the ruby laser since, as shown in Figure 3.3, the ruby laser can fire only after  $200\mu s$  have elapsed - the amount of time necessary for the flash lamps to energize. This is true for either the single pulse, as in the present case, or the double pulse mode of operation. Hence, in order for the laser to lase automatically at some time after impact in the  $0-30\mu s$  range, it would have to be triggered (signal sent to Master Sync) at some time prior to impact. This was done using a timing delay oscilloscope (Tektronix 535) as follows.

Prior to making the double exposure hologram, the time that it took the ball to go from the trigger laser beam to the plate was measured by an electronic counter. This is shown as  $T_{AC}$  in Figure 3.4. This distance traversed by the ball in going from A to C was approximately 1 inch and  $T_{AC}$  was typically in the .02 second range ( $20,000\mu s$ ). Upon specifying the time after plate impact to be observed,  $T_{IMPT}$ , and utilizing the fact that Pulse #2 of the laser fires at  $1000\mu s$  into the firing sequence, the delay time,  $T_{AB}$ , was determined from the relationship:

$$T_{AB} = T_{AC} + T_{IMPT} - 1000\mu s \quad (3.1)$$

The delay oscilloscope was then set so that a signal was sent to trigger the ruby laser after a delay of  $T_{AB}$  seconds. The Pockels cell voltage for Pulse #1 of the ruby laser was set to zero, thus eliminating Pulse #1 from the firing sequence.

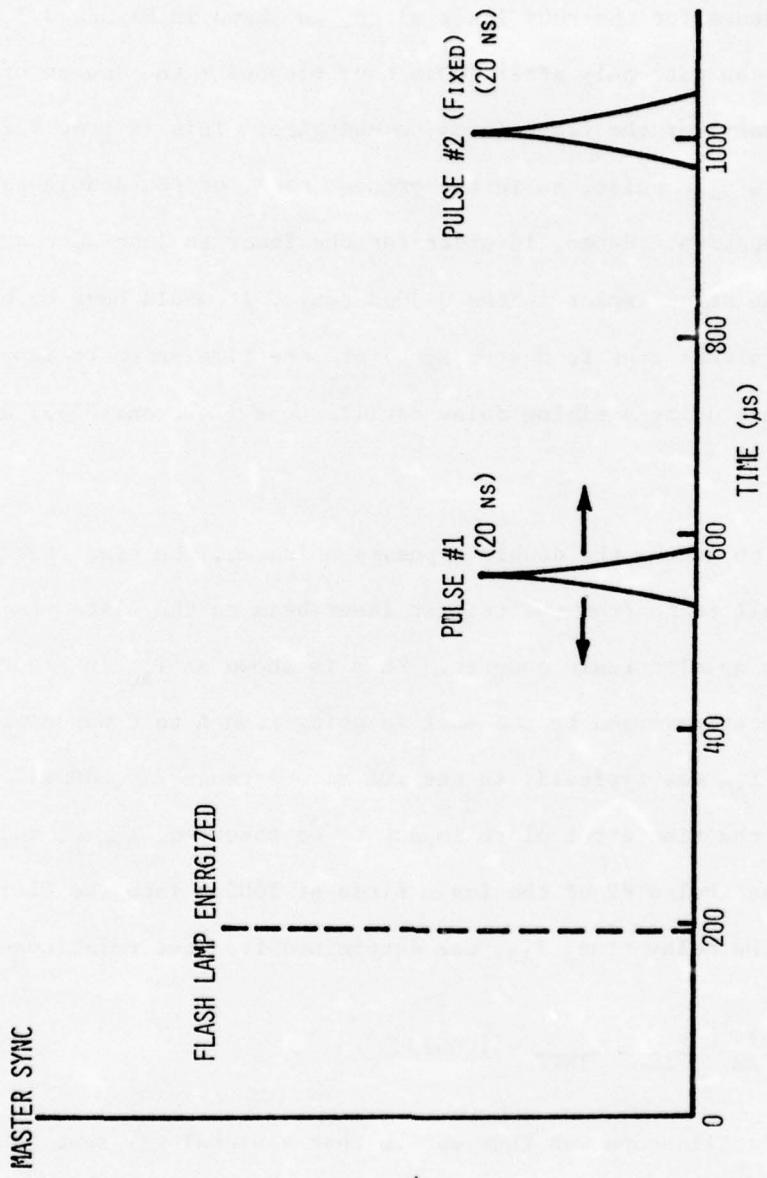


Figure 3.3 - Timing Sequence for Pulsed Ruby Laser

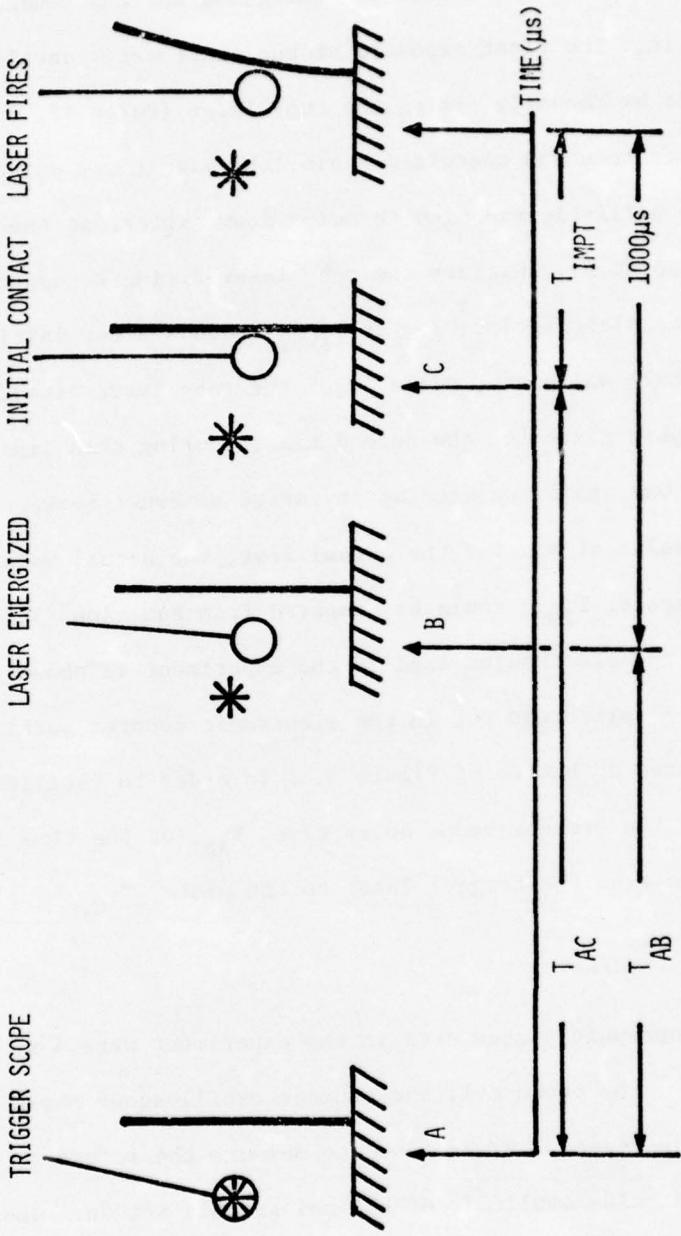


Figure 3.4 - Impact/Laser Timing Sequence

With the steps mentioned above carried out, the actual impact test was run. First, the magnet was energized and the pendulum attached to it. The first exposure of the stationary cantilever plate was then made by manually firing the ruby laser (Pulse #2, only). The ruby laser then was energized again, the magnet was switched off, allowing the ballistic pendulum to swing down, interrupt the trigger laser beam (point A), initiate the ruby laser firing sequence (point B), and impact the plate (point C). At  $T_{IMPT}$  seconds after initial contact between the ball and plate, Pulse #2 of the ruby laser fired, exposing the photographic plate for the second time. During this impact sequence, the time  $T_{AC}$  was again measured as it varied somewhat between tests. Knowing the value of  $T_{AC}$  for the actual test, the actual value of the time after impact,  $T_{IMPT}$  could be computed from equation (3.1). A schematic of the electronics used in the experiment is shown in Figure 3.5. A switch was put in the electronic counter portion of the circuit (located at bottom of Figure 3.5) in order to facilitate quick monitoring of the present scope delay time,  $T_{AB}$ , or the time it took the ball to go from the trigger laser to the plate,  $T_{AC}$ .

### 3.3 Hologram Processing

The photographic plates used in the experiment were 4"x5" Agfa-Gevaert 10E75. The photo cell and storage oscilloscope shown behind the hologram in Figure 3.5 were used to measure the reference to object beam ratio and pulse amplitude of the holographic set up. The beam ratio for the tests was approximately 2 to 1 (reference beam to object beam). The combination of photo cell and storage oscilloscope could only give

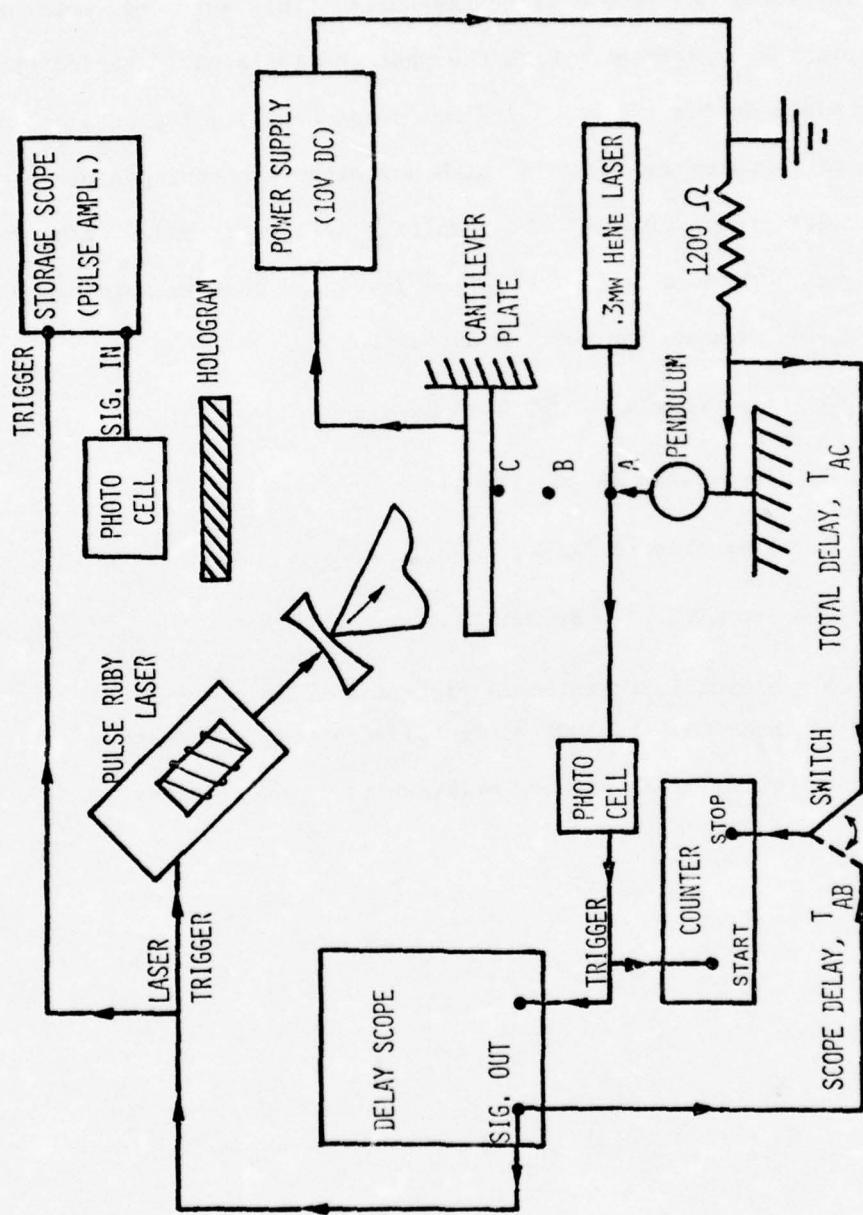


Figure 3.5 - Electronic Circuitry for Making a Double Exposure Hologram

relative light intensity measurements, i.e., the amplitude of the reference beam relative to the object beam or the relative amplitude between the first and second plate exposures. This sufficed, however, for the present experiment. With the photo cell placed 1" behind the hologram plate holder, "acceptable" holograms resulted for oscilloscope readings of .4 volts and .6 volts with and without a photographic plate in the holder, respectively. The resulting holograms tended to be dark but this was corrected by bleaching the developed photographic plates.

The developing process was carried out as follows:

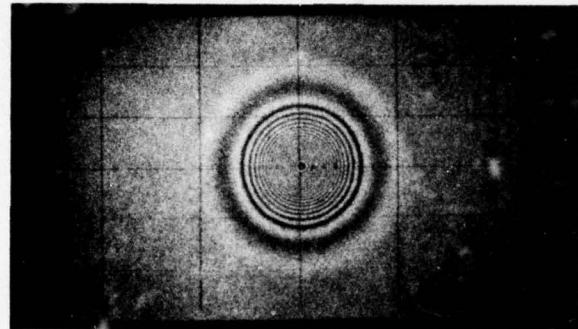
1. 4 minutes in Kodak D-19 developer;
2. 30 seconds in stop bath;
3. 3 minutes in fixer;
4. Dry with blow dryer;
5. Bleach in Potassium Ferricyanide (15g of  $K_3Fe(CN)_6$  in 1000 ml distilled water) - agitate until plate becomes milky white, approximately 1 minute.

SECTION IV

EXPERIMENTAL DATA REDUCTION AND RESULTS

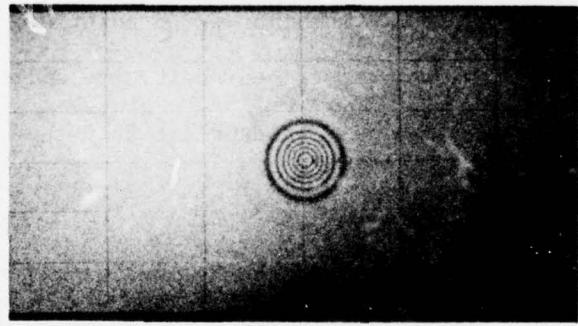
Figures 4.1 through 4.5 show the cantilevered plate's response for times after impact ranging from  $2\mu s$  to  $33\mu s$ . For the sake of increased fringe clarity, the photographs taken of the holograms show the immediate area of impact. Recall that the impact point lies on the vertical axis of the plate and 3 inches above the clamped base. The numbers in parentheses refer to the raw data numbering system used to denote each test run. The 6061-T6 aluminum plate was painted with a flat white paint and a grid having 1" by .5" increments was scribed on it. In addition,  $1/8"$  increments were scribed on the plate centerline from the impact point to 1" below it.

Referring to Figures 4.1 through 4.5, the fringes concentrically located around the impact point (ball impacting from rear) represent loci of constant displacement on the plate. The fringes are a contour map of the flexural waves caused by the impact. They travel outward with time until they reach the free edge of the plate at about  $T=12\mu s$  and are reflected. It is evident from the photographs that either the timing measurements are in error by as much as  $\pm 2\mu s$  or that there was some scatter in the magnitude and duration of the impulse load imparted to the plate by the steel ball pendulum. The latter reason is thought to be the case because of a permanent magnetic field that



2  $\mu\text{s}$

(91)



4  $\mu\text{s}$

(89)



6  $\mu\text{s}$

(90)

Figure 4.1 - Double Exposure Holograms of Cantilever Plate (2, 4, and 6 $\mu\text{s}$ )

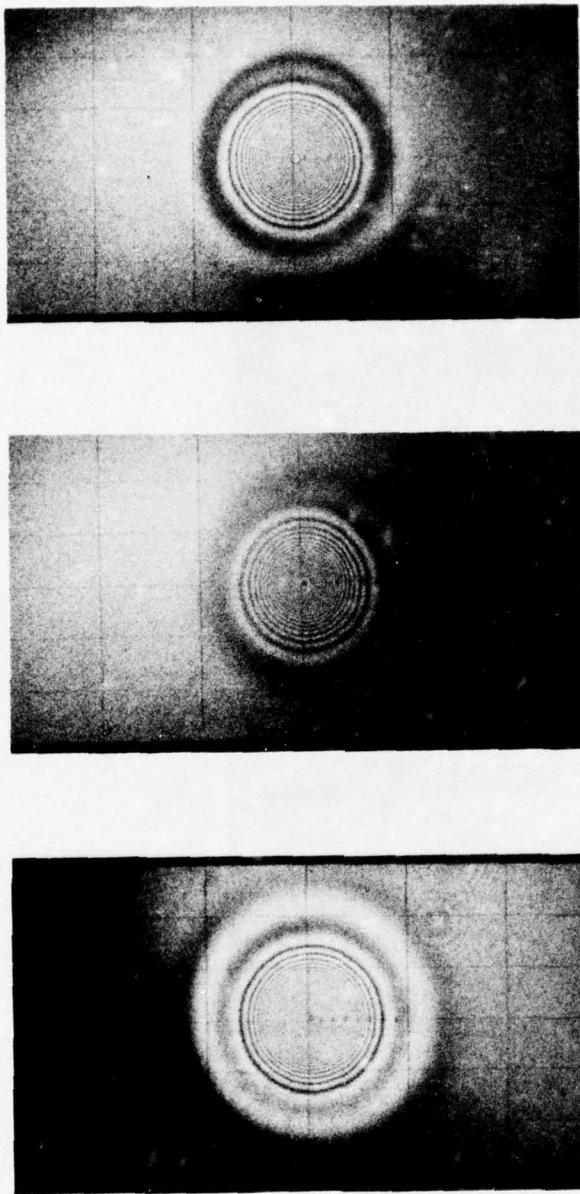
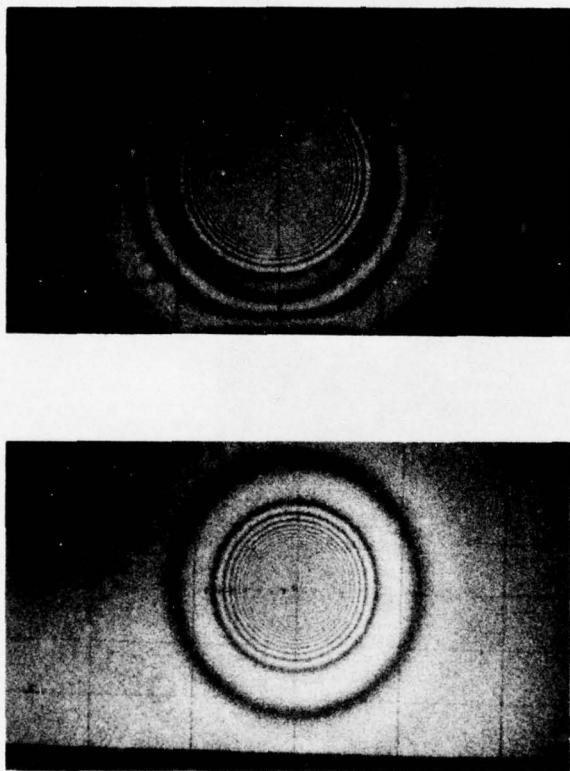


Figure 4.2 - Double Exposure Holograms of Cantilever Plate (9, 10, and 11 $\mu$ s)



12  $\mu\text{s}$  (107)      13  $\mu\text{s}$  (96)

Figure 4.3 - Double Exposure Holograms of Cantilever Plate (12 and 13 $\mu\text{s}$ )

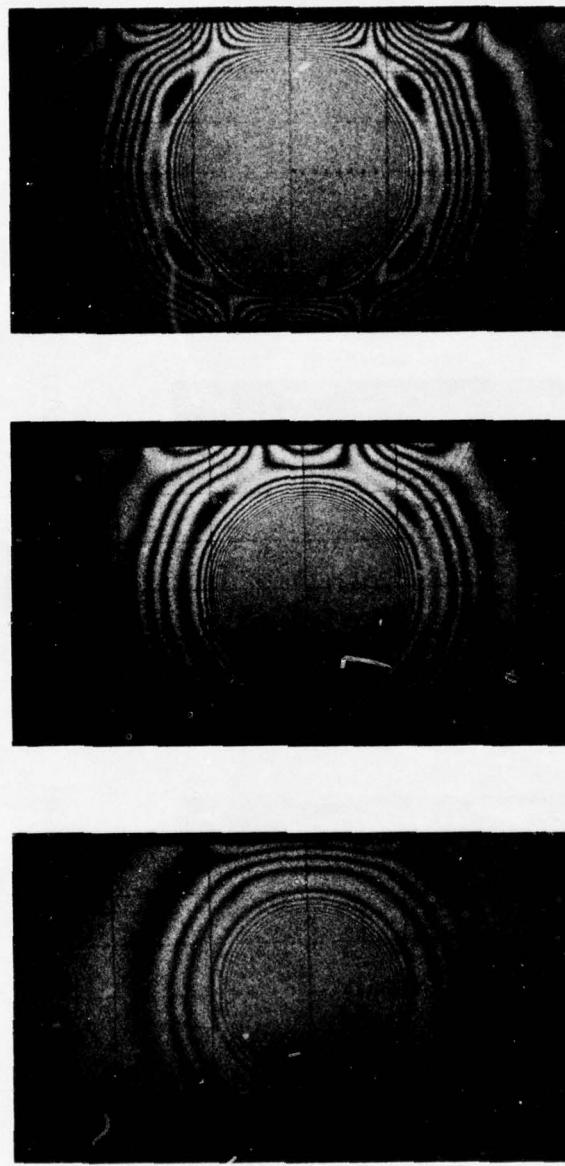


Figure 4.4 - Double Exposure Hologram of Cantilever Plate (16, 18, and 24μs)

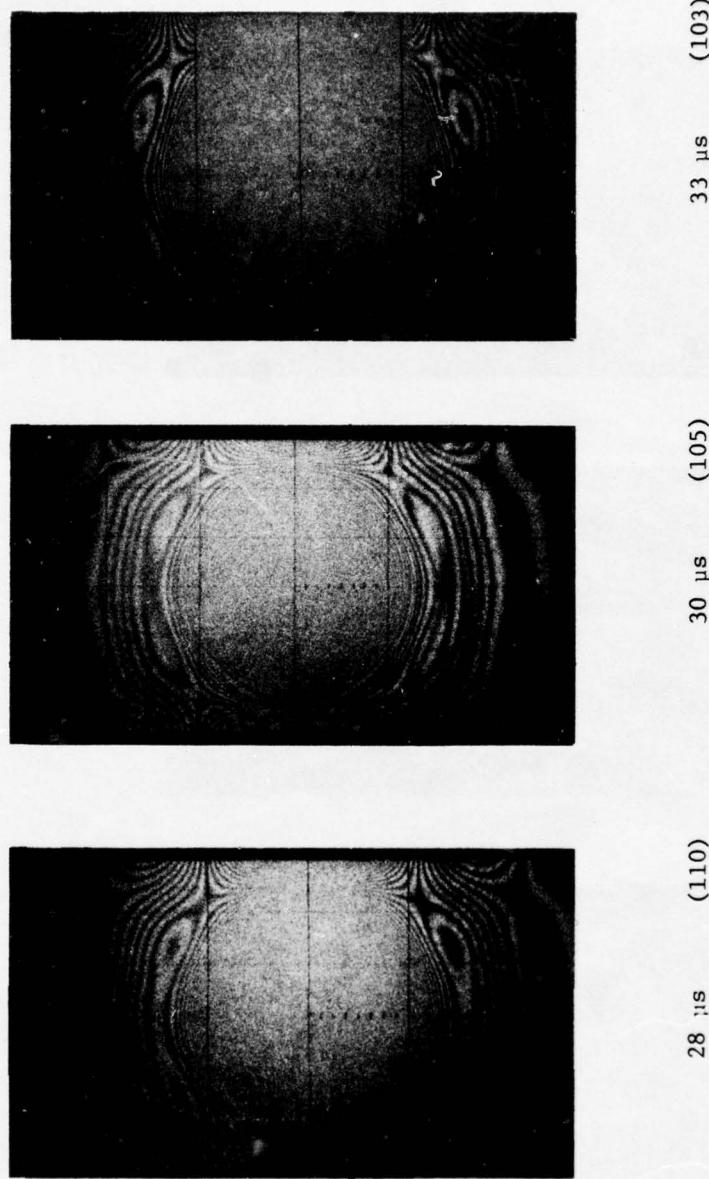


Figure 4.5 - Double Exposure Hologram of Cantilever Plate (28, 30, and 33 $\mu$ s)

was induced in the electromagnet used to release the steel ball. The permanent magnetic field varied somewhat throughout the duration of the impact tests. The magnetic force field would have the effect of slowing up the ball's release and, consequently, decreasing its impact force. This fact is corroborated by Figures 4.6 and 4.7 where the force time profile is seen for four successive ball impacts on a pressure transducer (Piezotronics, PCB 118A-B, 2 $\mu$ s rise time) temporarily imbedded in the plate at the impact point. The pressure amplitude (proportional to force) in test 1 is 20% less than the tests 2 through 4. While future work in this area should strive for a more repeatable loading system, the present data scatter was found to be acceptable within the scope of the present research effort. The load profile shown in Figures 4.6 and 4.7 was also utilized to determine the loading input for the finite element analysis (Section 5.1).

The fringe pattern position and the corresponding times after impact in Figures 4.1-4.5 can be used to compute the velocity of the flexural waves in the plate. Using the outermost visible fringe for times after impact ranging from 2 $\mu$ s to 13 $\mu$ s, one can get a plot of wave position as a function of time. The slope of this curve will be the flexural wave velocity. Using the fringe pattern positions and corresponding times in Figures 4.1 through 4.3, the curve shown in Figure 4.8 was generated. Because of the aforementioned scatter due to load repeatability, a linear least squares routine was used to generate the curve through the data points. The slope of the curve gives the flexural wave velocity as  $C_f = .1024 \text{ in}/\mu\text{s}$ .

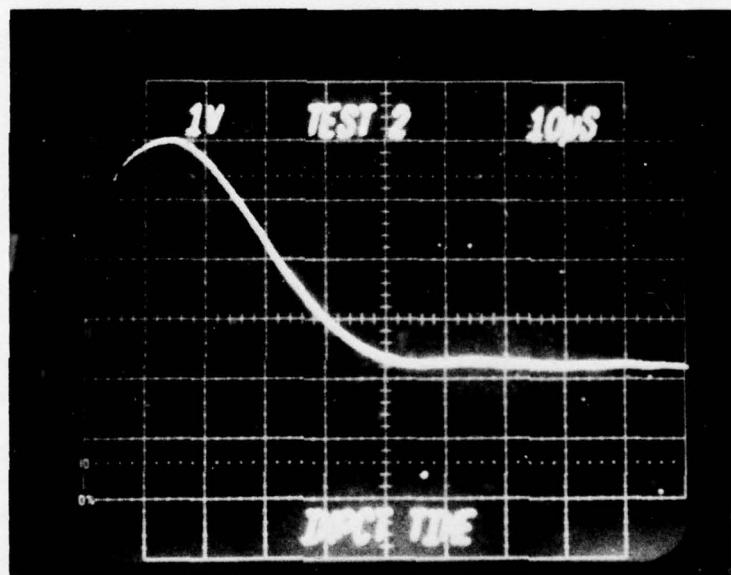
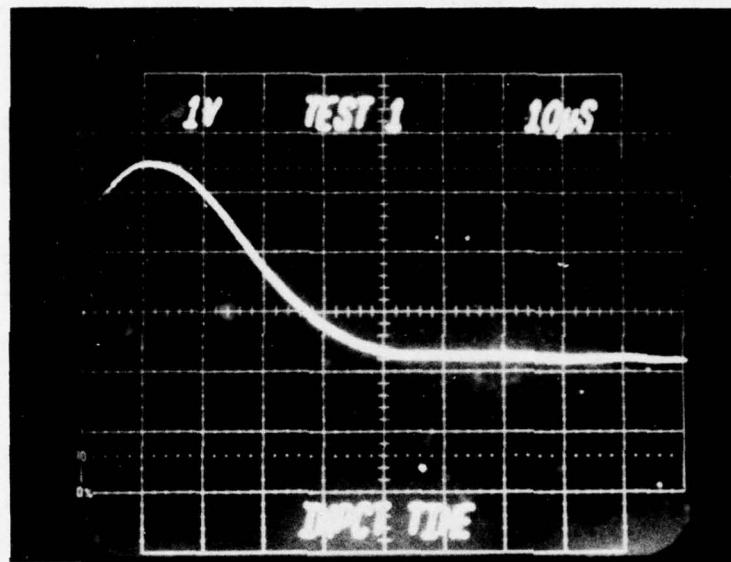


Figure 4.6 - Pressure Transducer Output at Impact Point Vs Time (Tests 1 and 2)

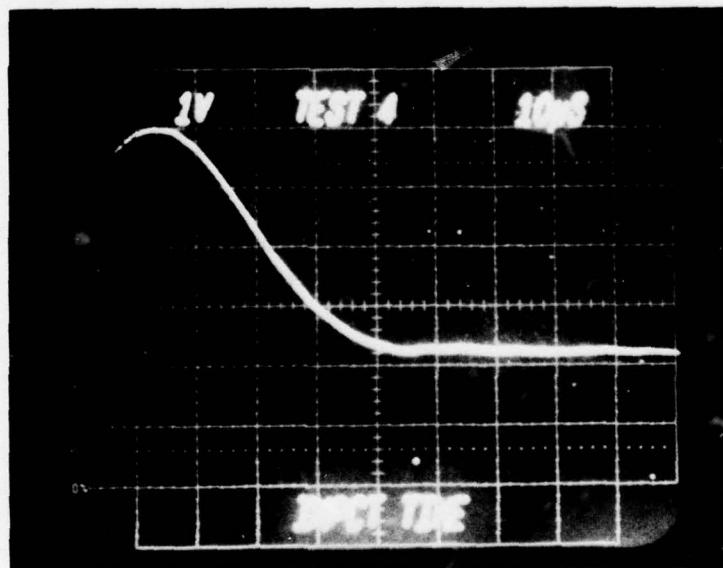
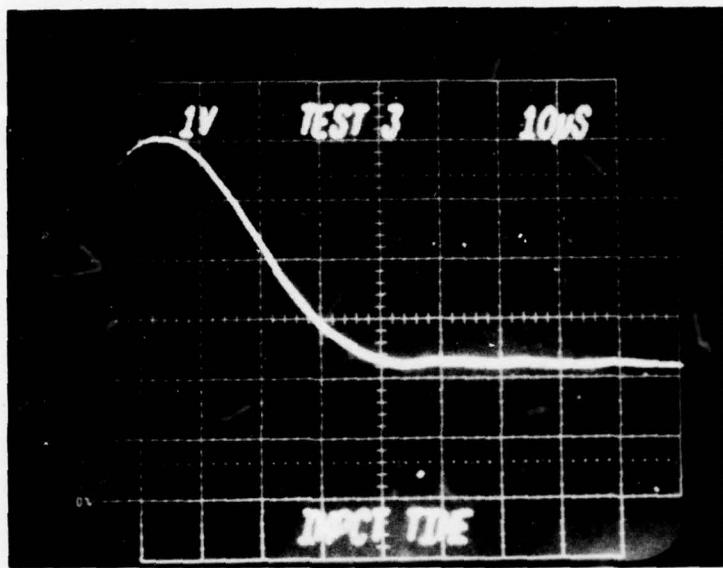


Figure 4.7 - Pressure Transducer Output at Impact Point  
Vs Time (Tests 3 and 4)

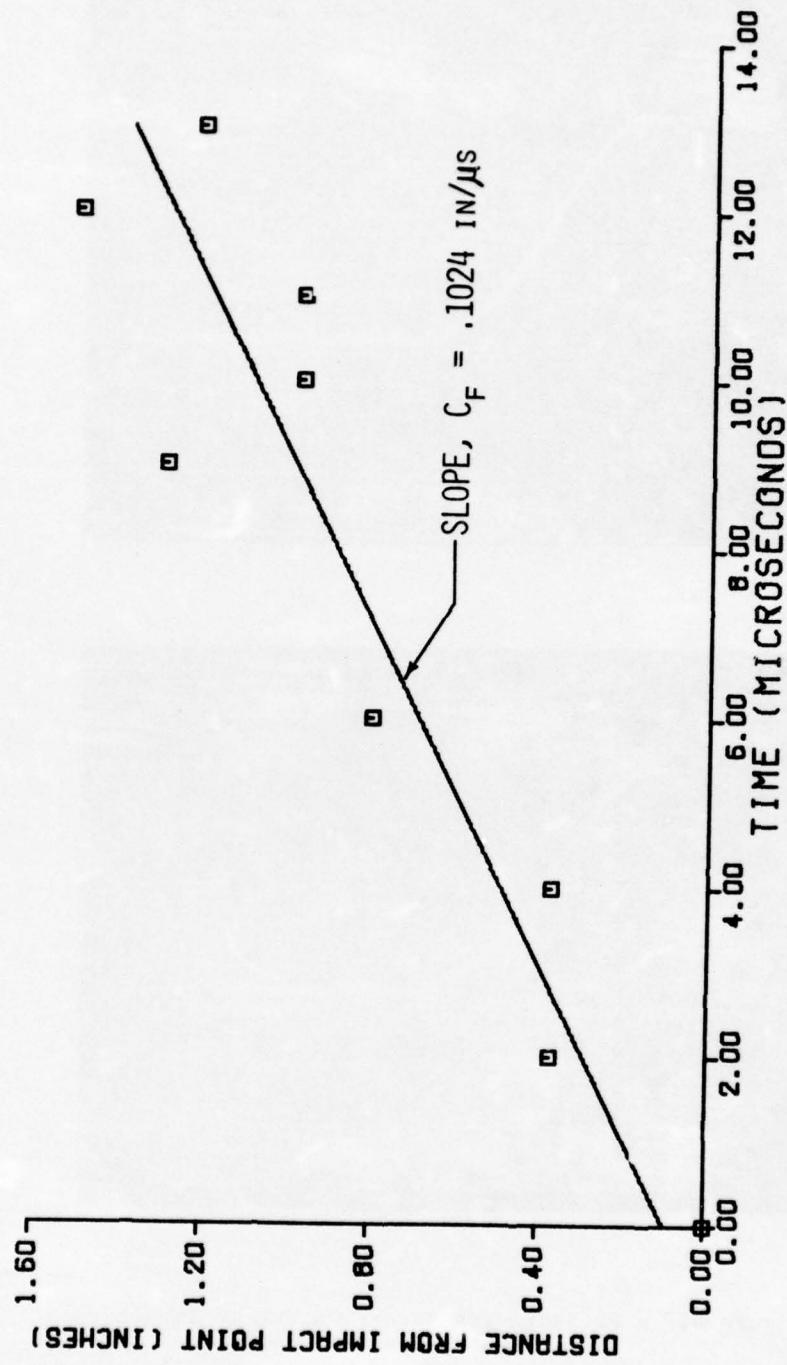


Figure 4.8 - Flexural Wave Position As a Function of Time After Impact

It is of interest to compare the experimental value of the flexural wave velocity to that obtained using the three-dimensional equations of elasticity (Ref. 2, 3, and 4). According to classical plate theory, the flexural wave velocity in an infinite plate approaches that of a Rayleigh surface wave when the wavelength,  $\lambda$ , becomes small compared with the plate thickness,  $h$ . In the case of the present impact tests, the steel ball made contact with the plate over a circular area of less than .03125 inches in diameter. Now, the wavelength,  $\lambda$ , is a function of the pulse shape and plate contact area, and if the pulse loading is broken into its Fourier components, the largest component's wavelength will be on the order of twice the diameter of the contact area. Hence, the smallest value of  $h/\lambda$  for the plate with  $h = .1875$  is  $h/\lambda = 3$ . All other values of  $h/\lambda$  for the higher Fourier components will be greater than this value. For values of  $h/\lambda > 3$ , the flexural wave velocity in a plate closely approximates that of a Rayleigh surface wave and can be obtained from the expression (Ref. 4).

$$C_f = .932 C_s \quad (\nu = 1/3) \quad (4.1)$$

where  $C_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+\nu)\rho}}$  is the shear wave velocity.

For the test plate;  $E = 1 \times 10^7$  psi,  $\nu = .3$ , and  $\rho = 2.587 \times 10^{-4}$  lbm. Placing these values into equation (4.1) yields a value of  $C_f = .112$  in/ $\mu$ s. This is within  $\pm 8.5\%$  of the experimental value.

The magnitude of the plate's displacement can be obtained from the fringe photographs using the expression (Ref. 5 and 6):

$$\vec{\delta} \cdot (\vec{n}_o + \vec{n}_v) = \frac{(2N \mp 1)\lambda}{2}, \quad \text{for } N = \pm 1, \pm 2, \pm 3, \dots \quad (4.2)$$

where  $\vec{\delta}$  - displacement vector

$\vec{n}_o$  - unit vector in direction from object  
to illumination source (object beam)

$\vec{n}_v$  - unit vector in direction from viewer  
(through hologram) to object

$\lambda$  - wavelength of laser used to make the  
hologram

N - fringe order

The vectors given by equation (4.2) are shown in the context of the present experimental geometry in Figure 4.9.

Carrying out the dot product in equation (4.2) yields:

$$|\vec{\delta}| |\vec{n}_o + \vec{n}_v| \cos(\vec{n}_o, \vec{n}_v) = \frac{(2N \mp 1)\lambda}{2} \quad (4.3)$$

letting  $|\vec{\delta}| \equiv \delta$  and using Figure 4.9 gives

$$|\vec{n}_o + \vec{n}_v| = |1.975 \vec{i} + .222 \vec{j}| = 1.987 \quad (4.4)$$

$$\cos(\vec{n}_o, \vec{n}_v) = .975 \quad (4.5)$$

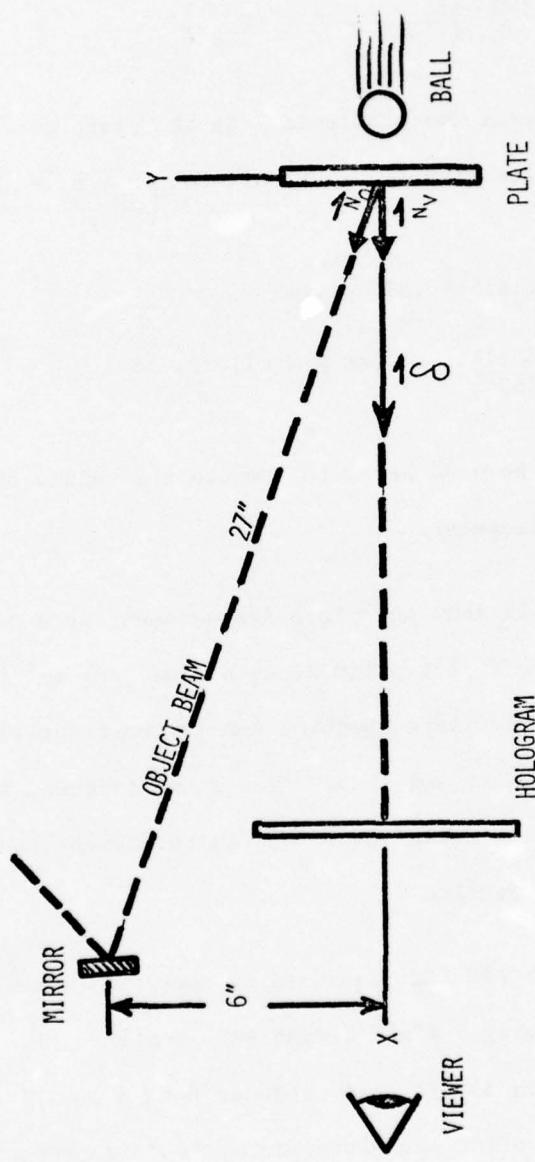


Figure 4.9 - Vector Diagram For Normal Displacement Computation

Hence, the displacement,  $\delta$ , in the direction that bisects  $\vec{n}_o$  and  $\vec{n}_v$  is:

$$\delta = \frac{(2N \mp 1)\lambda}{(2)(.975)(1.987)} = \frac{(2N \mp 1)\lambda}{3.874} \quad (4.6)$$

The displacement normal (perpendicular) to the plate surface differs from that given in equation (4.5) by only  $\cos\left(\frac{\vec{n}_o, \vec{n}_v}{2}\right) = .994$ .

Dividing equation (4.6) by .994 gives

$$\delta_n = \frac{(2N \mp 1)\lambda}{3.853}, \quad \text{for } N = \pm 1, \pm 2, \pm 3 \dots \quad (4.7)$$

Equation (4.7) will be used below to compute the values of the plate's normal displacement.

Figures 4.10-4.13 show the plate displacement as a function of the distance from the impact point along a line from the impact point to the free edge of the plate (Section A-A in the figures) for times after impact of 4, 6, 12, and 18 $\mu$ s. Also shown in these figures are the normal displacement curves based on finite element analysis which will be discussed in Section V.

Polaroid type 55 P/N film was used to photograph the double exposure holograms using a 4"x5" format view camera with a Polaroid film holder. Polaroid 55 P/N film produces both a positive and negative print. The negative print was placed in a standard photographic enlarger such that the enlarged view of the displacement fringes could be used to more accurately determine the corresponding displacement. Using the enlarger, fringes as high as N=70 could be

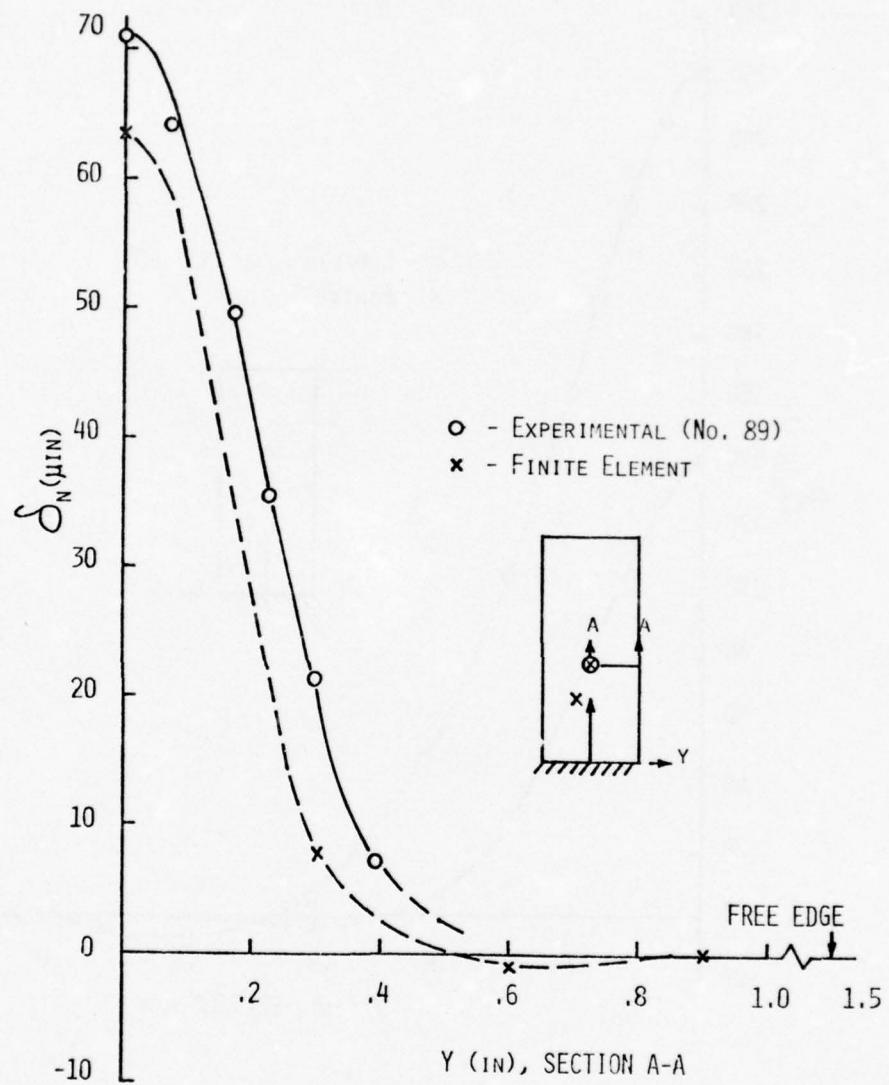


Figure 4.10 - Normal Displacement,  $\delta_n$ , Vs Distance From Impact Point, Y, at  $T=4\mu s$

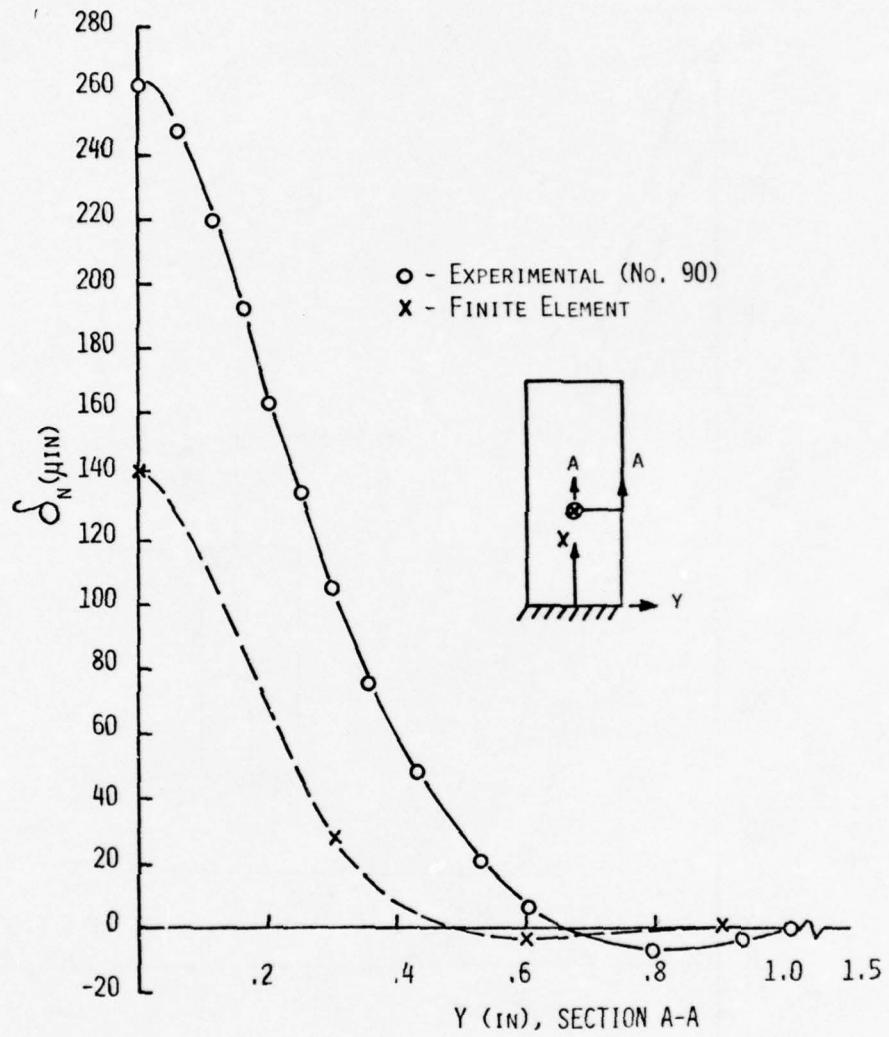


Figure 4.11 - Normal Displacement,  $\delta_n$ , Vs Distance From  
Impact Point, Y, at T=6us

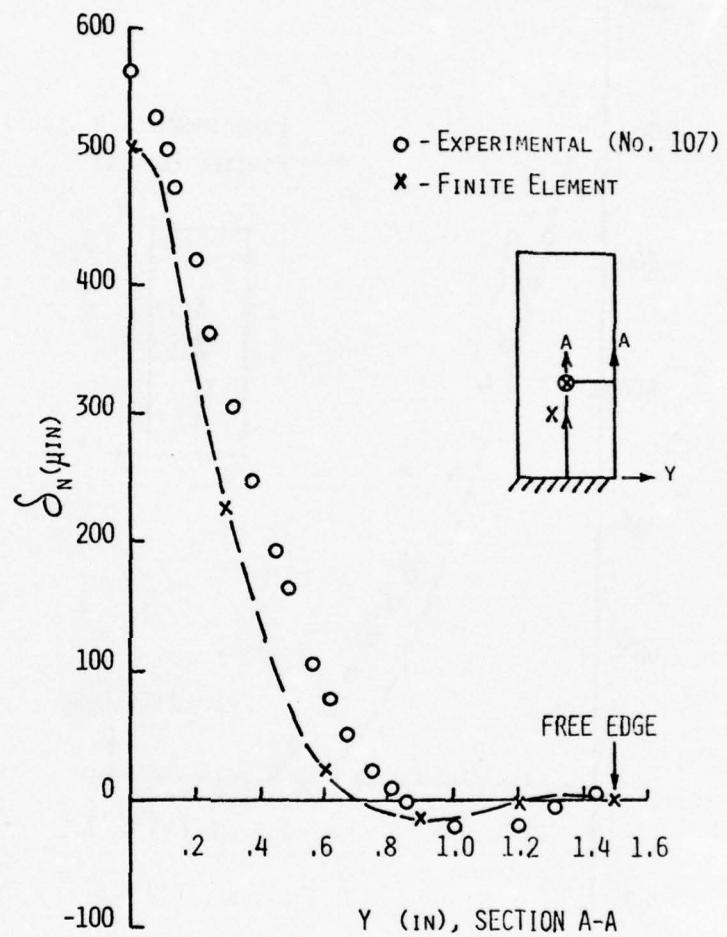


Figure 4.12 - Normal Displacement,  $\delta_n$ , Vs Distance From Impact Point, Y, at  $T=12\mu s$

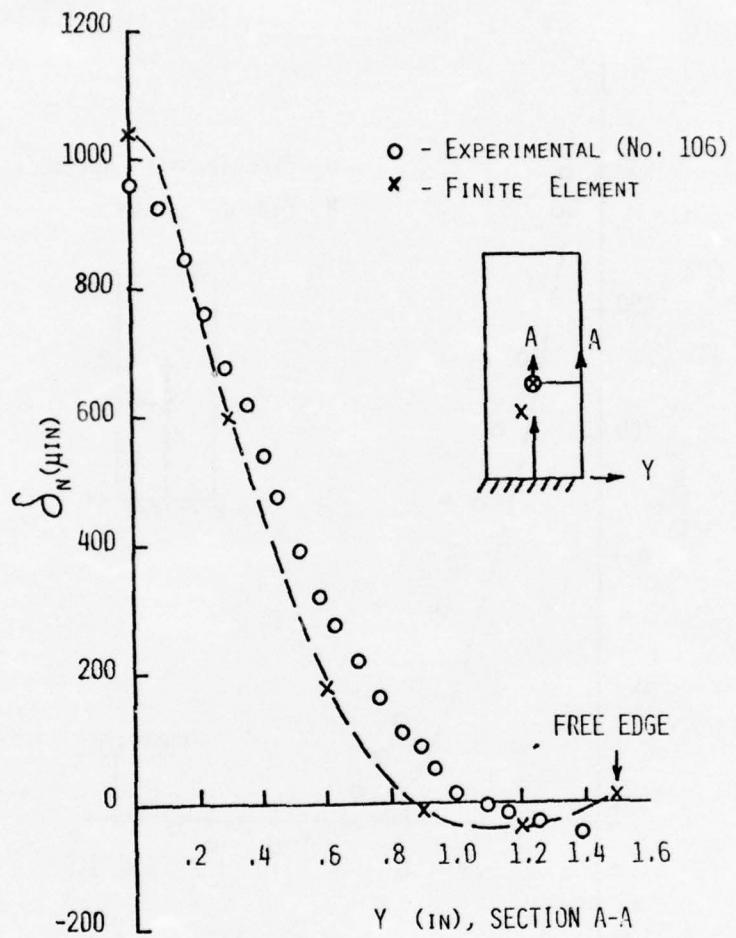


Figure 4.13 - Normal Displacement,  $\delta_n$ , Vs Distance From Point,  $Y$ , at  $T=18\mu s$

observed. (Note that this technique could be conveniently expanded to include a digital X-Y plotting table as the projecting surface for the enlarger.)

In contrast to time-average holography where the white fringe denoting zero displacement is the most intense and stands out clearly, the fringe representing zero displacement in double exposure holography is of the same intensity as its neighboring higher order fringes. Hence, in order to get a quantitative plot of the displacement based on a single hologram, some a priori information on the plate's displacement response is necessary. Referring to Figures 4.1, 4.2, and 4.3, the maximum plate displacement occurs at the impact point and decreases in magnitude as one travels outward from it. Since the flexural displacement is a wave, the positive displacement at the impact point will be followed by a smaller negative one at some distance from the impact point and then, as one travels further away from the impact center, a return to the undeformed, zero displacement, portion of the plate. The peak negative displacement manifests itself by a widening of the fringes where the slope of the negative displacement goes to zero. This can be seen in Figure 4.3 in the 12 $\mu$ s (107) photograph. Using this type of reasoning the plate's normal displacement could be plotted. While this approach was found to be sufficient for the simple deformation pattern that the plate experienced, more complex displacements would necessitate more sophisticated approaches such as multiple double exposure holograms. As an aside, another approach that could be used to determine the zero displacement fringe would be to use an optical bench telescope

to scan across the image of the hologram. By scanning along a horizontal line passing through the impact point, the concentrically located fringes will appear to converge toward one of the circular fringes. In other words, the impact point will appear to be a fringe "source" with fringes traveling toward the one stationary circular fringe. Fringes located outside the stationary circular fringe will appear to travel in the direction of the impact point and the stationary circular fringe. The stationary fringe is a loci of zero displacement and by viewing the convergence (traveling) characteristics of the adjacent fringes, it can be located.

Figure 4.14 shows a plot of the plate's normal displacement along its free edge (Section B-B) at  $T=24\mu s$  after impact. The displacement curve is based on the third fringe photograph shown in Figure 4.14 and shown enlarged in Figure 4.15. The fringes are numbered in Figure 4.15. Along the free edge, the undeformed plate was used as the zero reference point. In addition, fringes that curved from one point on the free edge to another provided a convenient indicator of points of equal displacement on the opposite sides of a hill or a valley.

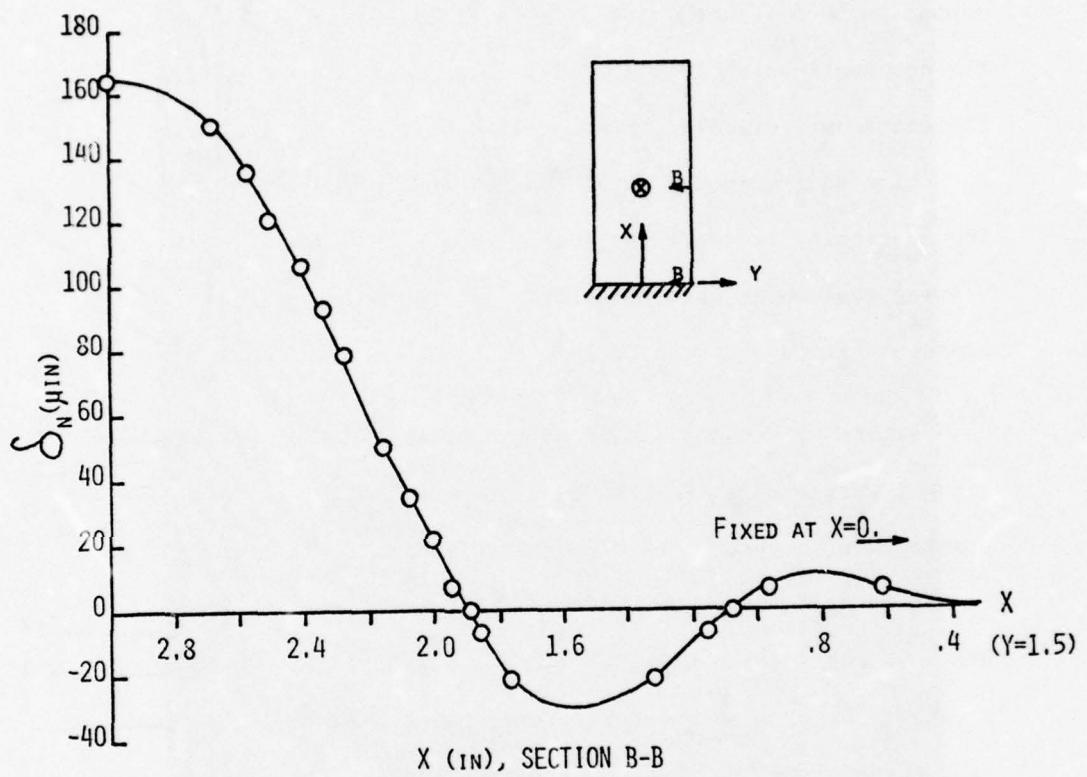


Figure 4.14 - Normal Displacement Along Plate Free Edge  
at  $T=24\mu s$

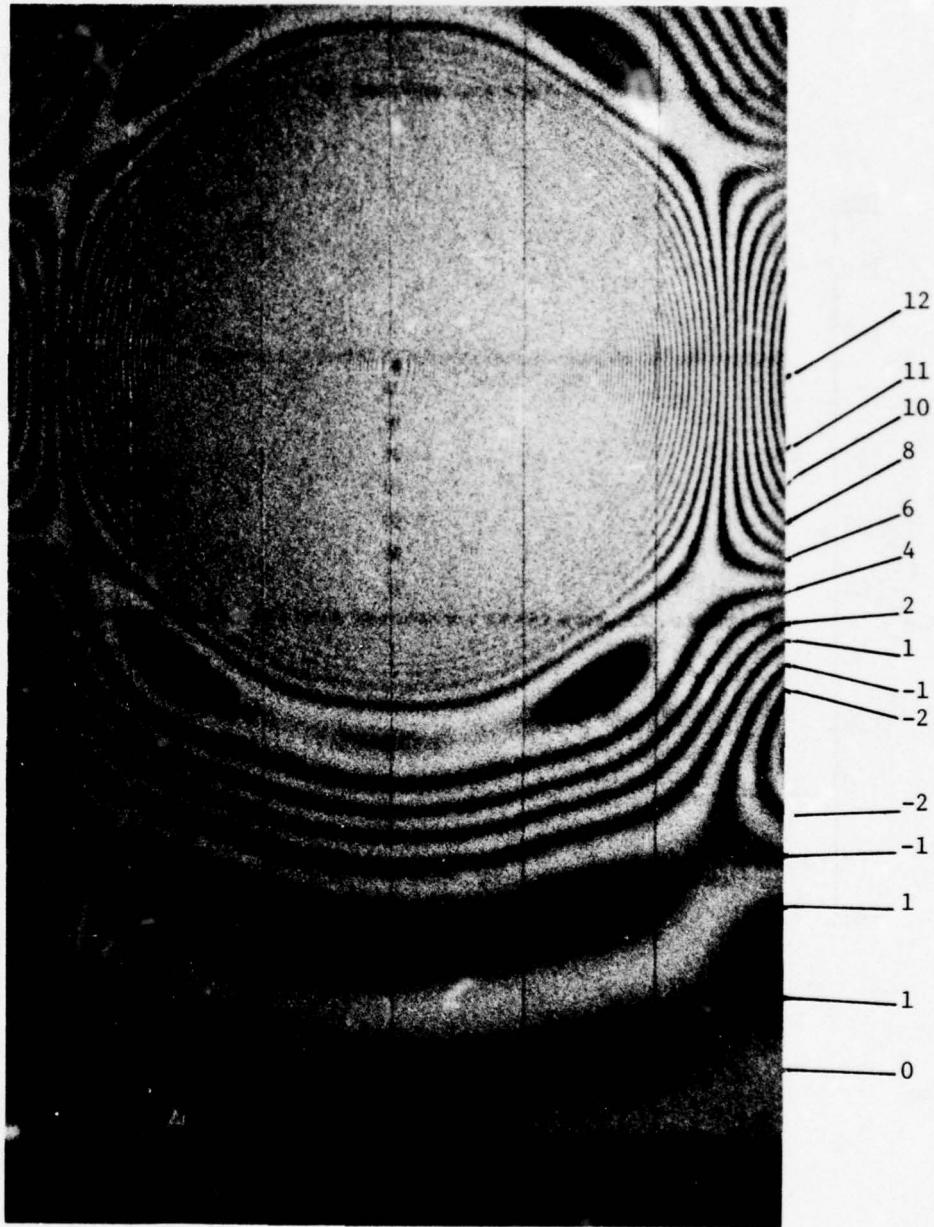


Figure 4.15 - Enlarged View of Impacted Plate at  $T = 24 \mu\text{s}$  Showing Numbered Fringes

## SECTION V

## FINITE ELEMENT ANALYSIS AND RESULTS

## 5.1 Finite Element Model

The numerical portion of the study was based on a finite element analysis of the cantilever plate using the general purpose finite element computer program, NASTRAN (Navy Nastran, Level 15.2.0). The model geometry and orientation for the cantilever plate is shown in Figure 5.1. The mesh consists of 304 nodes that connect the 165 quadrilateral plate elements (CQUAD2). The nodes at the base of the plate were fixed against both translation and rotation to simulate the cantilever condition. Because the impact load acts symmetrically with respect to the long axis of the plate, only half the plate was modelled with the nodes along the plate's axis of symmetry being fixed against asymmetrical motions, namely, translation in the Y direction and rotation about the X axis. These assumptions yield a finite element model having 957 degrees of freedom. Note that a refined mesh was used in the area about the impact point (shown by arrow). The plate response was essentially the same whether or not the refined mesh was used (thus demonstrating convergence) but better contour plots resulted when the finer mesh was used.

The transient analysis module of NASTRAN, Rigid Format 9, was used to carry out the analysis. When using the transient analysis module one can elect to use either a modal superposition technique or a direct integration of the nodal displacements. The latter

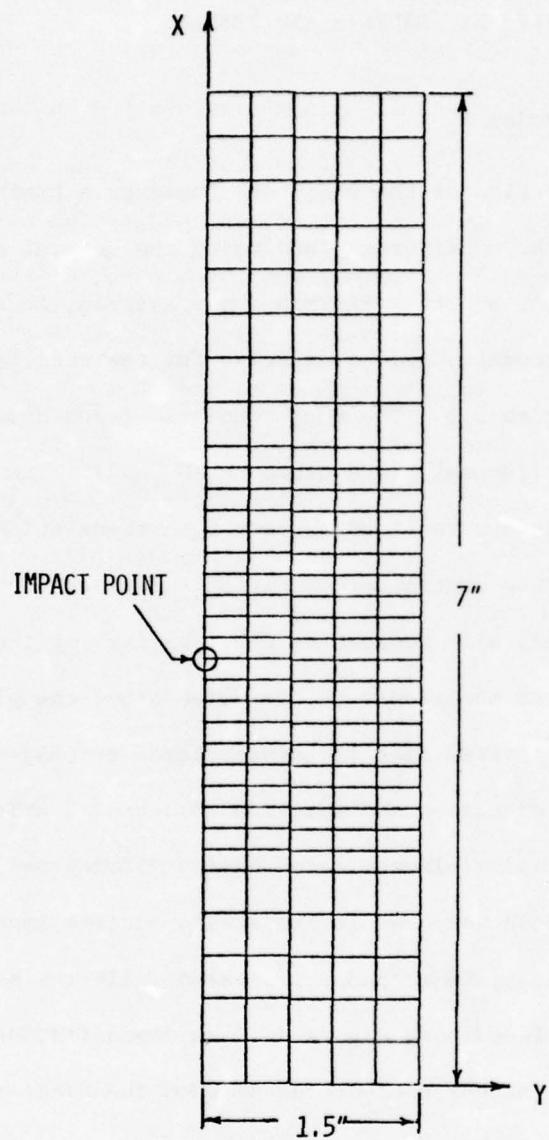


Figure 5.1 - Finite Element Mesh of Cantilever Plate

technique of direct integration was adopted for this study because it would have taken a prohibitive number of normal modes and frequencies to effectively model the plate response for an impact load that had a duration of 55 $\mu$ s. A good rule of thumb when using the modal superposition method is that both the integration step size and the period of the highest normal mode should be, at most, one-tenth the size of the force duration. For the present study, this would have required the highest mode of vibration to have a period of about 5 $\mu$ s, i.e., a natural frequency of  $2 \times 10^5$  Hz. This fact, coupled with the additional fact that the direct integration technique is inherently more accurate since it handles all degrees of freedom, lead to its choice as the solution technique.

The transient analysis module of NASTRAN accepts the forcing function in tabular form where the load amplitude and direction versus time are input for each node in the area of the load. For the present study, a single load in the normal (Z) direction was input as a function of time at the node designated by the arrow in Figure 5.1 (node number 171). The load profile was assumed to be the shape of a half sine wave (see Figures 4.6 and 4.7) having a duration of 55 $\mu$ s. By measuring the height of the ballistic pendulum at its release point and at its maximum rebound position from the plate, the amplitude of the half sine load can be obtained by equating the maximum kinetic energy to the maximum potential energy of the pendulum. For a pendulum of mass, m, being released at height,  $h_1$ , and rebounding to a height of  $h_2$ , equating the maximum potential and kinetic energies

yields a change in velocity of:

$$V_1 - V_2 = \sqrt{2g} (\sqrt{h_1} - \sqrt{h_2}) \quad (5.1)$$

where  $g$  is the acceleration of gravity.

The impulse of the force,  $F(t)$ , acting for a time,  $T$ , is

$$I = \int_0^T F(t) dt = m (V_1 - V_2). \quad (5.2)$$

For a force having a half sine wave profile,

$$F(t) = A \sin \left( \frac{\pi t}{T} \right) \quad (5.3)$$

where  $A$  is the force amplitude.

Utilizing equations (5.1) and (5.3) in equation (5.2) yields

$$I = \int_0^T A \sin \frac{\pi t}{T} dt = m \sqrt{2g} (\sqrt{h_1} - \sqrt{h_2}) \quad (5.4)$$

Carrying out the integration and solving for the amplitude gives:

$$A = \frac{\pi m \sqrt{2g}}{2T} (\sqrt{h_1} - \sqrt{h_2}) \quad (5.5)$$

The mass of the steel ball was  $1.335 \times 10^{-3}$  slugs. From Figure 3.1, it is seen that  $h_1 = 9.75"$ . The rebound height was measured by taking a photograph of the ball's trajectory while illuminating it with a high frequency strobe light. The height,  $h_2$ , was found to be  $.263"$ . Placing these values into equation (5.5)

yields an amplitude of  $A = 230 \text{ lbf}$ . Hence, the force on the plate is

$$F(t) = 230 \sin \left( \frac{\pi t}{55\mu s} \right) \quad (5.6)$$

Equation (5.6) was used in tabular form in NASTRAN. (This is done using the "DAREA" and "TABLED1 75" bulk data cards in NASTRAN as shown in the Appendix).

## 5.2 Results of the Finite Element Analysis

Using the finite element mesh, boundary conditions, and impact load profile described above, NASTRAN computed the plate displacement for specified times after impact. The output was in the form of displacements at specified nodes plus contour plots of the displacement for the entire plate. The normal plate displacement was plotted as a function of the distance ( $v$ ) from the impact point at  $X=3"$  for times after impact of 4, 6, 12, and  $18\mu s$ . For purposes of comparison with the experimental results, the four plots are shown in Figures 4.10 through 4.13 of Section IV as the dashed curves. The agreement between the experimental and finite element result is quite good except for  $T=6\mu s$ . This is felt to be due to a stronger than average impact load for the experimental curve. This agreement is corroborated by a look at Figure 5.2 where the displacement of the plate impact point is shown plotted as a function of time. A computer generated second order least squares curve fit the finite element data exactly, demonstrating a parabolic relationship between the impact point dis-

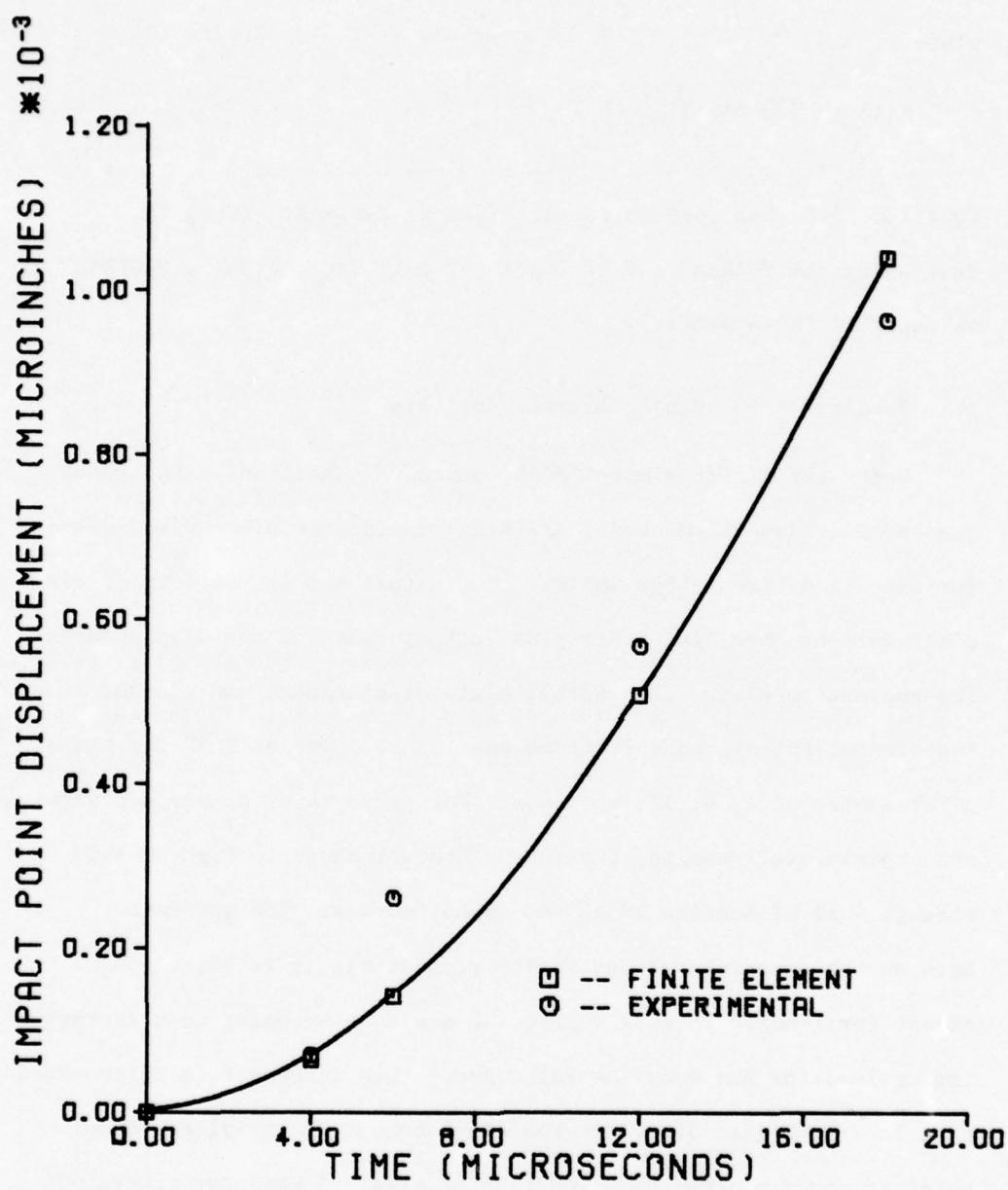


Figure 5.2 - Impact Point Displacement Vs Time

placement and time. The experimentally derived points closely follow this curve with the displacement at  $T=6\mu s$  showing the largest deviation, as one would expect.

Figures 5.3 through 5.5 show normal displacement contours of the plate response at times after impact of 6, 8, 12, 18, 24, and  $30\mu s$ . The values of the contours are given in Table 5.1. The trends demonstrated by the contour plots are in good agreement with the experimental results. Note in Figure 5.5 that reflection has started to take place off the free edge for  $T=30\mu s$ . While some of the symbols in the contour plots may be difficult to discern, the reader can be aided by the fact that contour numbers 1 through 29 represent increasing positive displacement and numbers 30 through 50 represent increasing negative displacement. This means that a loci of zero displacement lies between contours 1 and 31, exclusive.

TABLE 5.1

Normal Displacement Magnitude for NASTRAN Contour Plots (See Figures 5.3 - 5.5)

SYMBOL	DISPLACEMENT (IN.)	SYMBOL	DISPLACEMENT (IN.)
1	1.00E-05	26	9.00E-04
2	2.00E-05	27	9.50E-04
3	3.00E-05	28	1.00E-03
4	4.00E-05	29	1.05E-03
5	5.00E-05	30	-1.00E-05
6	6.00E-05	31	-2.00E-05
7	7.00E-05	32	-3.00E-05
8	8.00E-05	33	-4.00E-05
9	9.00E-05	34	-5.00E-05
10	1.00E-04	35	-6.00E-05
11	1.50E-04	36	-7.00E-05
12	2.00E-04	37	-8.00E-05
13	2.50E-04	38	-9.00E-05
14	3.00E-04	39	-1.00E-04
15	3.50E-04	40	-1.50E-04
16	4.00E-04	41	-2.00E-04
17	4.50E-04	42	-2.50E-04
18	5.00E-04	43	-3.00E-04
19	5.50E-04	44	-3.50E-04
20	6.00E-04	45	-4.00E-04
21	6.50E-04	46	-4.50E-04
22	7.00E-04	47	-5.00E-04
23	7.50E-04	48	-5.50E-04
24	8.00E-04	49	-6.00E-04
25	8.50E-04	50	-6.50E-04

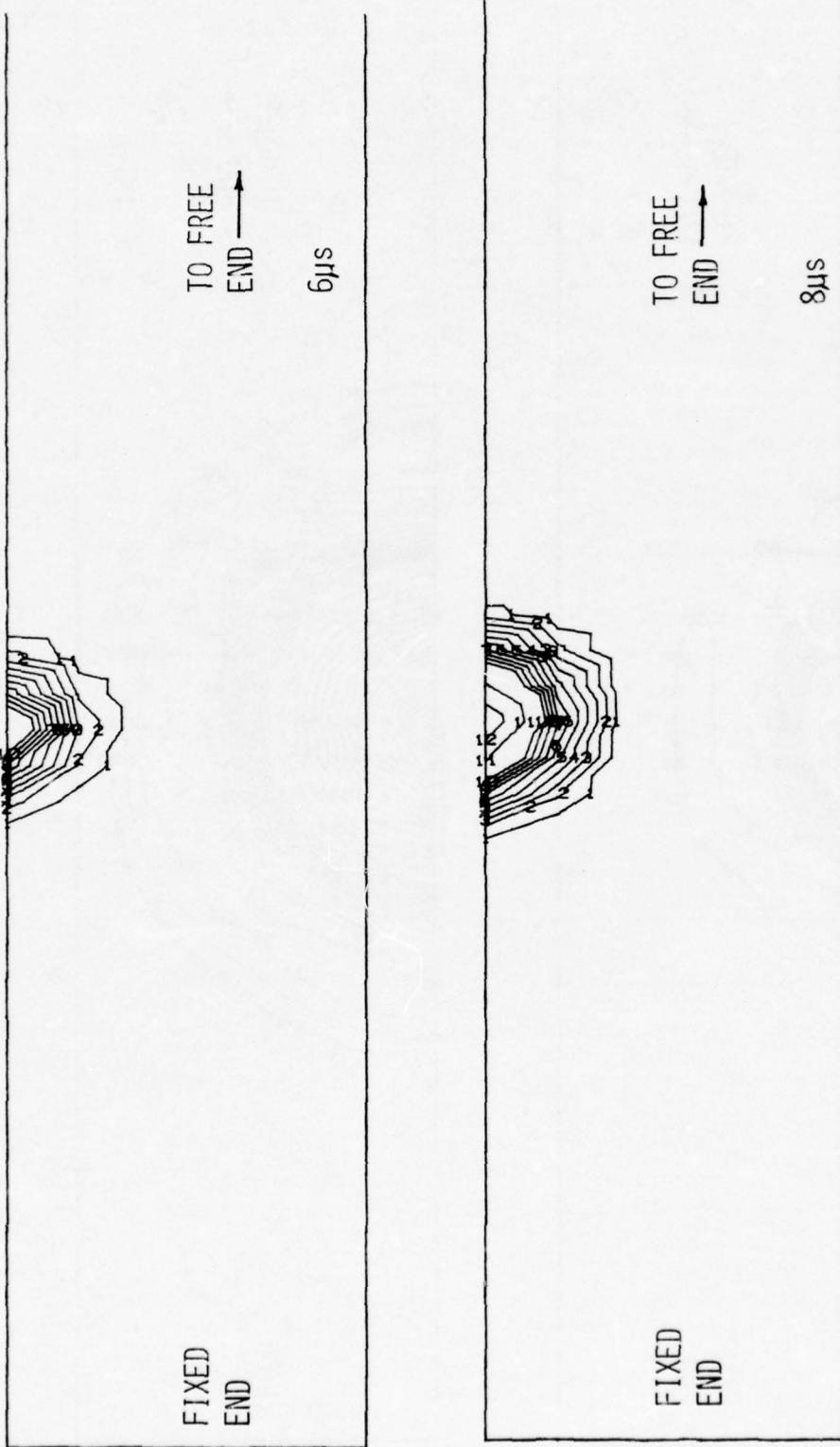


Figure 5.3 - NASTRAN Contour Plot of Normal Displacement at  $T=6\mu\text{s}$  and  $T=8\mu\text{s}$

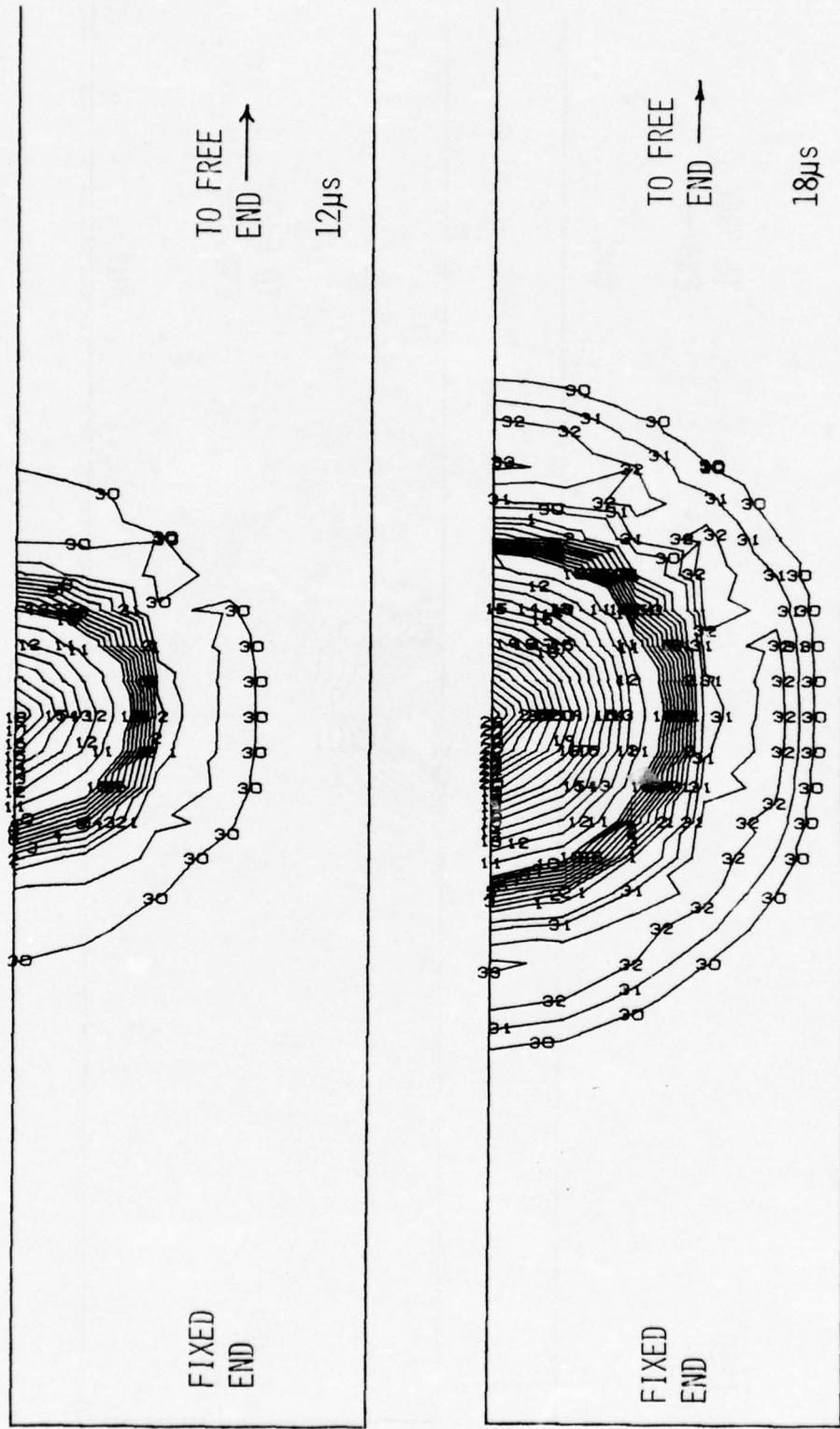


Figure 5.4 - NASTRAN Contour Plot of Normal Displacement at  $T=12\mu\text{s}$  and  $T=18\mu\text{s}$

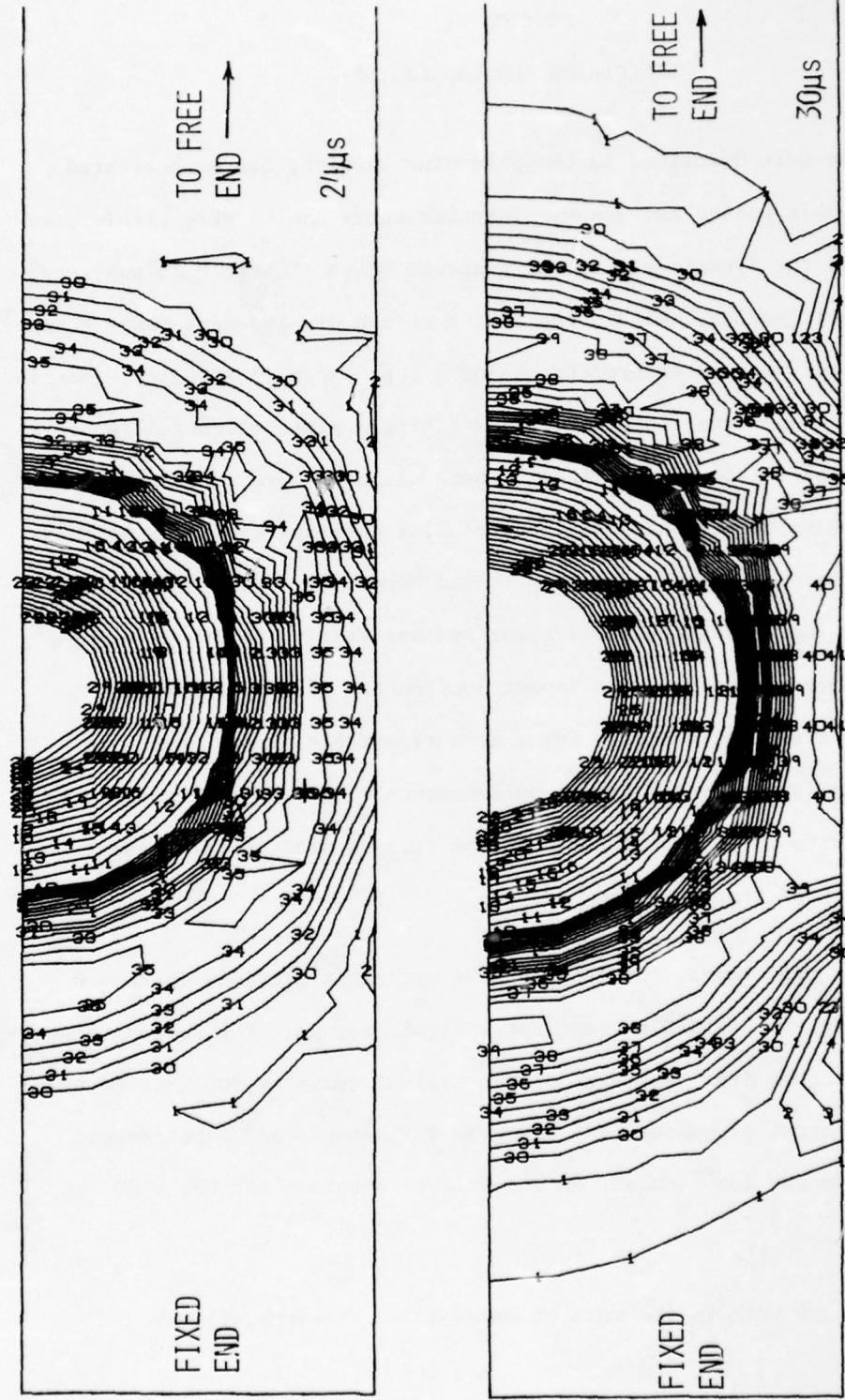


Figure 5.5 - NASTRAN Contour Plot of Normal Displacement at  $T=24\mu s$  and  $T=30\mu s$

## SECTION VI

## DISCUSSION AND CONCLUSION

The work described in the preceding sections has demonstrated that double pulsed holographic interferometry can be effectively used to study the dynamic structural response of an elastic body subjected to impact loading. Within the limits of the displacement range covered by pulsed laser interferometry using a ruby laser ( $5\text{-}1000\mu\text{in}$ ), quantitative displacement information describing a plate's initial response to an impact load was obtained. There was good agreement between the experimental tests and analytical results obtained using the NASTRAN finite element computer program (Rigid Format 9). Some scatter between individual tests did occur and was felt to be due to failure to accurately reproduce the impact load on the plate. Future work in this area should strive for a more repeatable impact load. In addition, experimental timing measurements should be increased to a sensitivity of  $\pm 0.1 \mu\text{s}$  instead of the  $\pm 0.5 \mu\text{s}$  used in the present experimental tests.

The good experimental/analytical agreement provides increased confidence in NASTRAN's transient analysis module. The good agreement does not come free, however. For a typical computer run (see Appendix), central processor (CP) time was 923 seconds and input/output (IO) time was 1360 seconds on the Wright-Patterson AFB CDC 6600 Computer.

Future work in the vein of the current research will use

the existing system to study turbine fan blade response to impact load. Some thought is also being given to utilizing the measurement of the plate flexural wave speed to determine elastic material properties of composites (say) and, also, to study material damping characteristics. Finally, plate displacements, at times greater than those dealt with in this report (2-30 $\mu$ s), could be studied using the double-pulse capability of AFAPL's ruby laser.

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AFAPL-TR-76-56

APPENDIX

NASTRAN Program Listing



COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

NASTRAN EXECUTIVE CONTROL DECK ECHO

IN-TRANSIT-PLATE NASTRAN  
01MAR16  
TIME 40  
CHKPT YES  
APP-GIFSP  
SOL 9,9  
END

COPY AVAILABILITY DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

NASTRAN EXECUTIVE CONTROL DECK ECHO

ECHO OF FIRST CARD IN CHECKPOINT DICTIONARY TO BE PUNCHED OUT FOR THIS PROBLEM

RESTART TWISTED ,PLATE + 7/ 276, 10042,

COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

```

PLATE TRANSIENT RESPONSE CASE CONTROL ECHO
CARD COUNT TITLE=PLATE TRANSIENT RESPONSE
2 SPC=2
3 TST=0=66
4 SET 2=176,165,154,143,132,121,110,99,88,77,66,55,44,33,22,11
5 METH08=1
6 SUBCASE 1
7 SURFACE=HALF-SINE-LOAD
8 QLOC0=70
9 DISP=2
10 PLOTID= FLAT PLATE / FINITE ELEMENT
11 OUTPUT4=PLT1
12 PLOTTER CALCOMP * MODEL 7651C5
13 SET 1=0.0002
14 VIEW 90***.99.
15 SCALE 4.5
16 MAXIMUM DEFORMATION *1
17 FINE ORIGIN 1+SET 1
18 CONTCUP 701SP LIST .JL01.1.JL02.0.000.3..JL03.0.000.5..JL04.6.
19 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**COPY MACHINES DO NOT PERMIT FULLY LEGIBLE PRODUCTION**

PLATE TRANSIENT RESPONSE CASE CONTROL DECK ECHO

\*\*\* USER INFORMATION MESSAGE: 207. BULK DATA NOT SORTED, XPORT WILL RE-ORDER DECK.

COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

PLATE TRANSIENT RESPONSE

SORTED BULK DATA ECHO.

6480	COUNT	1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..	9 ..	10
1	000A02	6	1	6	17	18	19	19	19	19	0
2-	000A02	7	1	7	18	19	19	19	19	19	0
3-	000A02	8	1	6	19	20	20	20	20	20	0
4-	000A02	9	1	9	20	21	21	21	21	21	10
5-	000A02	10	1	14	21	22	22	22	22	22	11
6-	000A02	16	1	17	28	29	29	29	29	29	18
7-	000A02	17	1	18	29	30	30	30	30	30	19
8-	000A02	18	1	19	30	31	31	31	31	31	20
9-	000A02	19	1	20	31	32	32	32	32	32	21
10-	000A02	20	1	21	32	33	33	33	33	33	22
11-	000A02	26	1	28	39	40	40	40	40	40	29
12-	000A02	27	1	29	40	41	41	41	41	41	30
13-	000A02	28	1	34	41	42	42	42	42	42	31
14-	000A02	29	1	31	42	43	43	43	43	43	32
15-	000A02	36	1	32	43	44	44	44	44	44	33
16-	000A02	36	1	39	50	51	51	51	51	51	40
17-	000A02	37	1	40	51	52	52	52	52	52	41
18-	000A02	38	1	41	52	53	53	53	53	53	42
19-	000A02	39	1	42	53	54	54	54	54	54	43
20-	000A02	40	1	43	54	55	55	55	55	55	44
21-	000A02	46	1	54	61	62	62	62	62	62	51
22-	000A02	47	1	51	62	63	63	63	63	63	52
23-	000A02	48	1	52	63	64	64	64	64	64	53
24-	000A02	49	1	53	64	65	65	65	65	65	54
25-	000A02	50	1	54	65	66	66	66	66	66	55
26-	000A02	56	1	61	72	73	73	73	73	73	62
27-	000A02	57	1	62	73	74	74	74	74	74	63
28-	000A02	58	1	63	74	75	75	75	75	75	64
29-	000A02	59	1	64	75	76	76	76	76	76	65
30-	000A02	60	1	65	76	77	77	77	77	77	66
31-	000A02	66	1	72	83	84	84	84	84	84	73
32-	000A02	67	1	73	94	95	95	95	95	95	74
33-	000A02	68	1	74	95	96	96	96	96	96	75
34-	000A02	69	1	75	96	97	97	97	97	97	76
35-	000A02	70	1	76	97	98	98	98	98	98	77
36-	000A02	76	1	83	94	95	95	95	95	95	84
37-	000A02	77	1	84	95	96	96	96	96	96	85
38-	000A02	78	1	85	96	97	97	97	97	97	86
39-	000A02	79	1	96	97	98	98	98	98	98	87
40-	000A02	80	1	97	98	99	99	99	99	99	88
41-	000A02	86	1	98	99	100	100	100	100	100	99
42-	000A02	97	1	95	106	107	107	107	107	107	96
43-	000A02	96	1	96	107	108	108	108	108	108	97
44-	000A02	99	1	97	108	109	109	109	109	109	98
45-	000A02	90	1	98	109	110	110	110	110	110	99
46-	000A02	96	1	105	116	117	117	117	117	117	106
47-	000A02	97	1	106	117	118	118	118	118	118	107
48-	000A02	98	1	107	118	119	119	119	119	119	108
49-	000A02	99	1	108	119	120	120	120	120	120	109
50-	000A02	100	1	109	120	121	121	121	121	121	110

COPY AVAILABLE TO BDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

PLAFFF TRANSIENT RESPONSE

SOFTED BULK DATA ECHO									
GAPD	COUNT	1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..
51-	COUA02	166	1	116	127	126	117	120	117
52-	COUA02	107	1	117	128	129	120	119	118
53-	COUAN2	106	1	116	129	130	120	119	119
54-	COUA02	109	1	119	130	131	121	121	121
55-	COUA2	115	1	124	131	132	121	121	121
56-	COUA02	116	1	127	130	139	120	120	120
57-	COUA02	117	1	128	139	140	129	129	129
58-	COUA02	118	1	129	140	141	130	130	130
59-	COUA02	119	1	131	141	142	131	131	131
60-	COUA02	120	1	131	142	143	132	132	132
61-	COUA02	126	1	136	149	156	139	139	139
62-	COUA02	127	1	136	150	151	140	140	140
63-	COUA02	128	1	144	151	152	141	141	141
64-	COUAR2	129	1	141	152	153	142	142	142
65-	COUA02	137	1	142	153	154	143	143	143
66-	COUA02	136	1	149	160	161	150	150	150
67-	COUA02	137	1	150	161	162	151	151	151
68-	COUAN2	138	1	151	162	163	152	152	152
69-	COUA02	139	1	152	163	164	153	153	153
70-	COUA02	140	1	153	164	165	154	154	154
71-	COUA02	146	1	164	174	172	161	161	161
72-	COUAR2	147	1	161	172	173	162	162	162
73-	COUAN2	148	1	162	173	174	163	163	163
74-	COUA02	149	1	163	174	175	164	164	164
75-	COUA62	156	1	164	175	176	165	165	165
76-	COUA02	156	1	171	182	183	172	172	172
77-	COUA02	157	1	172	183	184	173	173	173
78-	COUAN2	158	1	173	184	185	174	174	174
79-	COUA02	159	1	174	185	186	175	175	175
80-	COUA02	160	1	175	186	187	176	176	176
81-	COUA02	166	1	162	193	194	183	183	183
82-	COUAN2	167	1	163	194	195	184	184	184
83-	COUA02	168	1	164	195	196	185	185	185
84-	COUA02	169	1	165	196	195	186	186	186
85-	COUAN2	170	1	166	197	198	187	187	187
86-	COUAN2	171	1	167	198	199	188	188	188
87-	COUA02	172	1	168	199	200	189	189	189
88-	COUA02	173	1	169	200	201	190	190	190
89-	COUA02	174	1	170	201	202	191	191	191
90-	COUAN2	175	1	171	202	203	192	192	192
91-	COUAN2	176	1	172	203	204	193	193	193
92-	COUA02	177	1	173	204	205	194	194	194
93-	COUA02	178	1	174	205	206	195	195	195
94-	COUAN2	179	1	175	206	207	196	196	196
95-	COUAN2	180	1	176	207	208	197	197	197
96-	COUA02	181	1	177	208	209	198	198	198
97-	COUA02	182	1	178	209	210	199	199	199
98-	COUA02	183	1	179	210	211	200	200	200
99-	COUAN2	184	1	180	211	212	201	201	201
100-	COUAN2	185	1	212	212	213	202	202	202

COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

PLATE TRANSIENT RESPONSE      SORTED BULK DATA ECHO.

CARD COUNT	1	2	3	4	5	6	7	8	9	10
101-	SAUA92	266	1	226	237	238	227			
102-	COUAD2	207	1	227	238	239	228			
103-	SAUA92	266	1	228	239	240	229			
104-	COUAD2	219	1	229	240	241	230			
105-	SAUA92	216	1	236	241	242	231			
106-	COUAD2	216	1	237	248	249	233			
107-	SAUA92	217	1	238	249	250	239			
108-	COUAD2	216	1	239	250	251	240			
109-	SAUA92	219	1	240	251	252	241			
110-	COUAD2	220	1	241	252	253	242			
111-	SAUA92	226	1	248	259	260	249			
112-	COUAD2	227	1	249	260	261	250			
113-	SAUA92	228	1	250	261	262	251			
114-	COUAD2	229	1	251	262	263	252			
115-	SAUA92	236	1	252	263	264	253			
116-	COUAD2	236	1	259	270	271	260			
117-	COUAD2	237	1	260	271	272	261			
118-	COUAD2	238	1	261	272	273	262			
119-	COUAD2	239	1	262	273	274	263			
120-	COUAD2	246	1	263	274	275	264			
121-	COUAD2	246	1	264	275	276	265			
122-	COUAD2	247	1	271	282	283	272			
123-	COUAD2	248	1	272	283	284	273			
124-	COUAD2	249	1	273	284	285	274			
125-	COUA..	25..	1	274	285	286	275			
126-	COUAD2	256	1	281	292	293	282			
127-	COHAD2	257	1	282	293	294	283			
128-	COUAD2	258	1	283	294	295	284			
129-	COHAD2	259	1	284	295	296	285			
130-	COUA..	26..	1	285	296	297	286			
131-	COHAD2	266	1	292	303	304	293			
132-	COUAD2	267	1	293	304	305	294			
133-	COHAD2	268	1	294	305	306	295			
134-	COUAD2	269	1	295	306	307	296			
135-	COUAD2	270	1	296	307	308	297			
136-	COUAD2	276	1	303	314	315	304			
137-	COHAD2	277	1	314	325	316	305			
138-	COUAD2	278	1	315	316	317	306			
139-	COHAD2	279	1	316	317	318	307			
140-	COUAD2	280	1	317	318	319	308			
141-	COUA92	286	1	314	325	326	315			
142-	COUAD2	297	1	315	326	327	316			
143-	COHAD2	298	1	316	327	328	317			
144-	COUAD2	299	1	317	328	329	318			
145-	SAUA92	295	1	318	329	330	319			
146-	COUAD2	296	1	325	336	337	326			
147-	SAUA92	297	1	326	337	338	327			
148-	COUAD2	298	1	327	338	339	328			
149-	COHAD2	299	1	328	339	340	329			
150-	COUAD2	300	1	329	340	341	330			
	COUAD2	301	1	330	341	342	331			

COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

PLATE TRANSIENT RESPONSE

S O R T E D   B U L K   D A T A   E C H O											
CAF-D	COUNT	1	2	3	4	5	6	7	8	9	10
151-	6004002	366	3	336	4	347	348	337			
152-	CQUAD2	307	1	337	348	349	349	338			
153-	6004002	363	1	338	349	350	350	339			
154-	CQUAD2	309	1	335	350	351	351	340			
155-	6004002	331	1	345	351	352	352	341			
156-	CQUAD2	316	1	347	358	359	359	348			
157-	6004002	337	1	348	359	360	360	349			
158-	CQUAD2	316	1	349	360	361	361	350			
159-	6004002	319	1	354	361	362	362	351			
160-	CQUAD2	320	1	351	362	363	363	352			
161-	6004002	326	1	358	369	370	370	359			
162-	CQUAD2	327	1	359	370	371	371	360			
163-	6004002	328	1	360	371	372	372	361			
164-	CQUAD2	329	1	361	372	373	373	362			
165-	6004002	324	1	362	373	374	374	363			
166-	DA-EA	65	171	3	236.						
167-	EIGR	1	INV	4	15000.	11	11				
168-	*EIG		MAX								
169-	GASST										
170-	GFID	6									
171-	GFID	7									
172-	GRID	8									
173-	GRID	9									
174-	GRID	10									
175-	GRID	11									
176-	GRID	17									
177-	GRID	18									
178-	GRID	19									
179-	GRID	20									
180-	GRID	21									
181-	GFID	22									
182-	GFID	28									
183-	GRID	29									
184-	GFID	30									
185-	GFID	31									
186-	GRID	32									
187-	GFID	33									
188-	GFID	39									
189-	GFID	46									
190-	GFID	41									
191-	GFID	42									
192-	GFID	43									
193-	GFID	44									
194-	GFID	50									
195-	GFID	51									
196-	GRID	52									
197-	GFID	53									
198-	GFID	54									
199-	GFID	55									
200-	GFID	61									

COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

PLATE TRANSIENT RESPONSE

S O R T E D   B U L K   D A T A   E C H O :											
GAP#	COUNT	1	2	3	4	5	6	7	8	9	10
264-	GRID 62	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500
265-	GRID 63	1.6500	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
266-	GRID 64	1.5000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
267-	SPID 65	1.0500	1.0200	1.0200	1.0200	1.0200	1.0200	1.0200	1.0200	1.0200	1.0200
268-	GRID 66	1.5500	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
269-	GRID 71	1.6500	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
270-	GRID 72	1.6500	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
271-	GRID 74	1.6500	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
272-	GRID 75	1.6500	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
273-	GRID 76	1.6500	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
274-	GRID 77	1.6500	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
275-	GRID 83	1.8000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
276-	GRID 84	1.8000	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
277-	GRID 85	1.8000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
278-	GRID 86	1.8000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
279-	GRID 87	1.8000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
280-	GRID 88	1.8000	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
281-	GRID 94	1.9500	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
282-	GRID 95	1.9500	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
283-	GRID 96	1.9500	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
284-	GRID 97	1.9500	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
285-	GRID 98	1.9500	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
286-	GRID 99	1.9500	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
287-	GRID 105	2.1000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
288-	GRID 106	2.1500	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
289-	GRID 107	2.1000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
290-	GRID 108	2.1000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
291-	GRID 110	2.1000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
292-	GRID 111	2.2500	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
293-	GRID 117	2.2500	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
294-	GRID 118	2.2500	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
295-	GRID 119	2.2500	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
296-	GRID 120	2.2500	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
297-	GRID 121	2.2500	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
298-	GRID 127	2.4000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
299-	GRID 128	2.4000	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
300-	GRID 129	2.4000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
301-	GRID 130	2.4000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
302-	GRID 131	2.4000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
303-	GRID 132	2.4000	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
304-	GRID 133	2.5000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
305-	GRID 134	2.5000	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
306-	GRID 135	2.5000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000	.6000
307-	GRID 136	2.5000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000	.9000
308-	GRID 137	2.5000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
309-	GRID 138	2.5000	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660	1.5660
310-	GRID 140	2.5510	.6100	.6100	.6100	.6100	.6100	.6100	.6100	.6100	.6100
311-	GRID 141	2.5550	.9669	.9669	.9669	.9669	.9669	.9669	.9669	.9669	.9669
312-	GRID 142	2.5550	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
313-	GRID 143	2.5556	1.5666	1.5666	1.5666	1.5666	1.5666	1.5666	1.5666	1.5666	1.5666
314-	GRID 145	2.7710	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
315-	GRID 151	2.7710	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600	.3600
316-	GRID 152	2.7710	.6100	.6100	.6100	.6100	.6100	.6100	.6100	.6100	.6100

COPY AVAILABLE TO EDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

AFAPL-TR-76-56

S O R T E D   B U L K   D A T A   E C H O '										
PLATE TRANSIENT RESPONSE		C A R A								
COU NT	GRID	1	•	152	•	2	•	3	•	4
251-	GRID	153		2.7000		• 9606		• 6000		• 6000
252-	GRID	154		2.7100		1.2000		• 0000		
253-	GRID	155		2.7400		1.5666		• 0000		
254-	GRID	160		2.6500		• 0000		• 0000		
255-	GRID	161		2.6500		• 3600		• 6000		
256-	GRID	162		2.8500		• 6000		• 0000		
257-	GRID	163		2.8500		• 9000		• 6000		
258-	GRID	164		2.8500		1.2000		• 0000		
259-	GRID	165		2.8500		1.5666		• 0000		
260-	GRID	171		3.0000		• 0000		• 0000		
261-	GRID	172		3.4440		• 3600		• 6000		
262-	GRID	173		3.0000		• 6000		• 0000		
263-	GRID	174		3.6000		• 9000		• 6000		
264-	GRID	175		3.6000		1.2000		• 0000		
265-	GRID	176		3.6000		1.5666		• 0000		
266-	GRID	182		3.1500		• 0000		• 0000		
267-	GRID	183		3.1500		• 3600		• 6000		
268-	GRID	184		3.1500		• 6000		• 0000		
269-	GRID	185		3.4500		• 9000		• 6000		
270-	GRID	186		3.1500		1.2000		• 0000		
271-	GRID	187		3.4500		1.5666		• 0000		
272-	GRID	193		3.3000		• 0000		• 0000		
273-	GRID	194		3.3000		• 3600		• 6000		
274-	GRID	195		3.3000		• 6000		• 0000		
275-	GRID	196		3.3000		• 9000		• 6000		
276-	GRID	197		3.3000		1.2000		• 0000		
277-	GRID	198		3.3000		1.5666		• 0000		
278-	GRID	204		3.4500		• 0000		• 0000		
279-	GRID	205		3.4500		• 3600		• 6000		
280-	GRID	206		3.4500		• 6000		• 0000		
281-	GRID	207		3.4500		• 9000		• 6000		
282-	GRID	208		3.4500		1.2000		• 0000		
283-	GRID	209		3.4500		1.5666		• 0000		
284-	GRID	215		3.6000		• 0000		• 0000		
285-	GRID	216		3.6000		• 3600		• 6000		
286-	GRID	217		3.6000		• 6000		• 0000		
287-	GRID	218		3.6000		• 9000		• 6000		
288-	GRID	219		3.6000		1.2000		• 0000		
289-	GRID	221		3.6000		1.5666		• 0000		
290-	GRID	226		3.7500		• 0000		• 0000		
291-	GRID	227		3.7500		• 3600		• 6000		
292-	GRID	228		3.7500		• 6000		• 0000		
293-	GRID	229		3.7500		• 9000		• 6000		
294-	GRID	230		3.7500		1.2000		• 0000		
295-	GRID	231		3.7500		1.5666		• 0000		
296-	GRID	237		3.0000		• 0000		• 0000		
297-	GRID	238		3.0000		• 3600		• 6000		
298-	GRID	239		3.0000		• 6000		• 0000		
299-	GRID	240		3.0000		• 9000		• 6000		
300-	GRID	241		3.0000		1.2000		• 0000		

COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION

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-PLATE TRANSIENT RESPONSE-

S O R T E D   B U L K   D A T A   E C H O .											
CARD	COUNT	1	2	3	4	5	6	7	8	9	10
36-	GRID	242									
36-1	GRID	248	4.0530	.0000							
36-2	GRID	249	4.6506	.3666							
36-3	GRID	250	4.0510	.6100	.3900						
36-4	GRID	251	4.6490	.9660	.0060						
36-5	GRID	252	4.0500	.2010	.0000						
36-6	GRID	253	4.6494	.5600	.6666						
36-7	GRID	254	4.0210	.0010	.0000						
36-8	GRID	260	4.6200	.3066	.0000						
36-9	GRID	261	4.0210	.6100	.0000						
36-10	GRID	262	4.6246	.9666	.0060						
36-11	GRID	263	4.0200	.1200	.0000						
36-12	GRID	264	4.6210	.5600	.6666						
36-13	GRID	270	4.3510	.0000	.0000						
36-14	GRID	274	4.3500	.3469	.5046						
36-15	GRID	277	4.3500	.6000	.0000						
36-16	GRID	278	4.3546	.9666	.0060						
36-17	GRID	279	4.3546	.9666	.0060						
36-18	GRID	279	4.3500	.1200	.0000						
36-19	GRID	279	4.3500	.1200	.0000						
36-20	GRID	285	4.6150	.5600	.6666						
36-21	GRID	286	4.6150	.0000	.0000						
36-22	GRID	287	4.6150	.3066	.0000						
36-23	GRID	287	4.6150	.6000	.0000						
36-24	GRID	287	4.6150	.9666	.0060						
36-25	GRID	287	4.6150	.9666	.0060						
36-26	GRID	292	4.6125	.0000	.0000						
36-27	GRID	293	4.6125	.3066	.0000						
36-28	GRID	294	4.6125	.6000	.0000						
36-29	GRID	295	4.6125	.9666	.0060						
36-30	GRID	295	4.6125	.1200	.0000						
36-31	GRID	296	4.6125	.5600	.6666						
36-32	GRID	297	4.6125	.0000	.0000						
36-33	SPID	303	5.1250	.0000	.0000						
36-34	SPID	304	5.1250	.3066	.0000						
36-35	SPID	305	5.1250	.6000	.0000						
36-36	SPID	305	5.1250	.9666	.0060						
36-37	SPID	307	5.1250	.1200	.0000						
36-38	GRID	310	5.1250	.5600	.6666						
36-39	GRID	314	5.4375	.0000	.0000						
36-40	GRID	315	5.4375	.3066	.0000						
36-41	GRID	316	5.4375	.6000	.0000						
36-42	GRID	317	5.4375	.9666	.0060						
36-43	GRID	318	5.4375	.1200	.0000						
36-44	GRID	325	5.7510	.0000	.0000						
36-45	GRID	326	5.7510	.3066	.0000						
36-46	GRID	327	5.7510	.6000	.0000						
36-47	GRID	328	5.7510	.9666	.0060						
36-48	GRID	329	5.7510	.1200	.0000						
36-49	GRID	331	5.7510	.5600	.6666						
36-50	GRID	331	5.7510	.0000	.0000						
36-51	GRID	331	5.7510	.3066	.0000						
36-52	GRID	331	5.7510	.6000	.0000						
36-53	GRID	331	5.7510	.9666	.0060						
36-54	GRID	331	5.7510	.1200	.0000						
36-55	GRID	331	5.7510	.5600	.6666						

**COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION**

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PLATE TRANSIENT RESPONSE

S O F T E D   B U L K   D A T A   E C H O

CARD		1	2	3	4	5	6	7	8	9	10
351-	GRID	337									
352-	GRID	338									
353-	GRID	339									
354-	GRID	340									
355-	GRID	341									
356-	GRID	342									
357-	GRID	343									
358-	GRID	344									
359-	GRID	345									
360-	GRID	346									
361-	GRID	347									
362-	GRID	348									
363-	GRID	349									
364-	GRID	350									
365-	GRID	351									
366-	GRID	352									
367-	GRID	353									
368-	GRID	354									
369-	GRID	355									
370-	GRID	356									
371-	GRID	357									
372-	GRID	358									
373-	GRID	359									
374-	MAT1	1	1.07		.3						
375-	ZACAM	LNGDSS	16								
376-	PNUAC2	1	1	.1875							
377-	SPC1	2	4	17	20	39	50	61	72	*42	
378-	+A2	83	94	105	116	127	134	149	160	*32	
379-	+B2	171	182	193	204	215	226	237	248	*22	
380-	+C2	259	270	281	292	303	314	325	336	*02	
381-	+D2	347	350	369							
382-	SPR1	2	123456	6	THRU	11					
383-	TABL#01	75									
384-	+A75	0.L	3.0-6								
385-	+B75	12.0-6	1.6330	15.0-6							
386-	+C75	24.0-6	1.9801	27.0-6	1.9906	27.5-6	1.0001	28.0-6	1.9996	*075	
387-	+D75	31.0-6	1.9801	34.0-6	1.9919	37.0-6	1.9953	37.5-6	1.9957	*075	
388-	+E75	43.0-6	1.6330	46.0-6	1.4917	49.0-6	1.3350	52.0-6	1.17.5	*F75	
389-	+F75	55.0-6	6.1600	ENDT							
390-	TLOAC1	75	65								
391-	TEST	60	55	1.0-6	1						
	ENDATA										